THE UNIVERSITY OF KANSAS SPACE TECHNOLOGY LABORATORIES
2291 Irving Hill Dr.— Campus West Lawrence, Kansas 66044
Telephone:

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# SURFACE CONFIGURATION AS AN EXPLANATION FOR LITHOLOGY-RELATED CROSS-POLARIZED RADAR IMAGE ANOMALIES

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James R. McCauley



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# TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

## ABSTRACT


Radars ordinarily transmit either horizontally or vertically polarized radiation and receive the same polarization transmitted. Because planetary surfaces return the two polarizations differently, and because components orthogonal to those transmitted may also be observed, experiments had been initiated as early as 1966 to determine the value of multiple polarization images to geologists. One problem that has persisted since the development of multipolarized radar is the cause or causes of differential depolarization which is expressed as tonal reversals between like- and cross-polarized images of certain outcrops. On AN/APQ-97 Ka-band radar imagery, rocks producing anomalously low returns on the cross-polarized image could be classed into three general types: (1) certain geologically recent lava flows (late Pleistocene and Holocene), (2) some Tertiary volcanics and (3) certain massive sandstones. Differential depolarization has been produced by volcanic rocks of various compositions including rhyolite, rhyodacite, dacite, andesite, and basalt. The sandstones which are responsible for an anomalous cross-polarized return include eolian sandstones and terrestrially derived arkoses. As is apparent, composition is diverse in this group of rocks, as is nearly every other lithologic character, including grain size, grain orientation, internal structures, etc. This has led to the conclusion that differential depolarization is not directly caused by any compositional factor. However, the study of aerial photos and subsequent field observation have led to the conclusion that the weathering and other surface characteristics of the outcrops are responsible for their appearance on multipolarized imagery.

It is believed that these three rock types, for differing reasons, produce terrains in which radar return is dominated by specular reflection from planar surfaces. For a specular reflector to be recorded on the radar image, its orientation should be orthogonal to the path of the impinging radar; and for such an orientation, the depolarized component of the reflected radar energy is at a minimum. The result would be a

higher return on the like-polarized image and a lower return on the cross-image. This is in compliance with the observed behavior of the three rock types mentioned above.

Outcrops of the three rock types share certain features; planar rock surfaces that are large in comparison with the wavelength of the incident radar are abundant and detrital material and vegetation are of secondary importance; the planar surfaces appear to significantly contribute to the returning radar energy, this energy maintaining a constant polarization; the outcrop areas are of sufficient size and sufficiently uniform character to be delineated on small scale K-band imagery.

CHAPTER 1

# INTRODUCTION

Side-looking airborne radar (SLAR) has been well documented as a useful geologic tool. All-weather capability, broad coverage, together with continually improving geometric fidelity and resolution make SLAR imagery ideal for reconnaissance studies. Proper interpretation of SLAR imagery requires a knowledge of the factors determining the strength of radar return. As a result, many facets of energy-target interaction have been studied. With the development of multipolarized radar, an additional system parameter was introduced which required evaluation. Initial studies of multipolarized radar imagery uncovered lithology-related tonal reversals that appeared to be of potential geologic value. This study was undertaken in order to determine the significance of polarization anomalies as they appear on Ka-band multipolarized SLAR imagery.

## FUNDAMENTALS OF SIDE-LOOKING AIRBORNE RADAR

Although SLAR imagery appears photographic in nature, it is actually a record of the varying intensity with which diverse parts of the earth's surface return an impinging microwave signal. Figure 1 shows an area being imaged by a SLAR system. All the apparatus is carried aboard an airplane moving with a velocity Va. A transmitter generates pulses of radio frequency (RF) energy which are propagated by a directional antenna (A) one at a time as a block of energy (B) at the speed of light and in a direction orthogonal to the path of the aircraft. A target on the ground such as point (a) when irradiated by the RF energy will return a portion of the transmitted energy back to the antenna. At a later time, point (b) will be irradiated by the same pulse and will likewise return a portion of the transmitted energy. The same is true

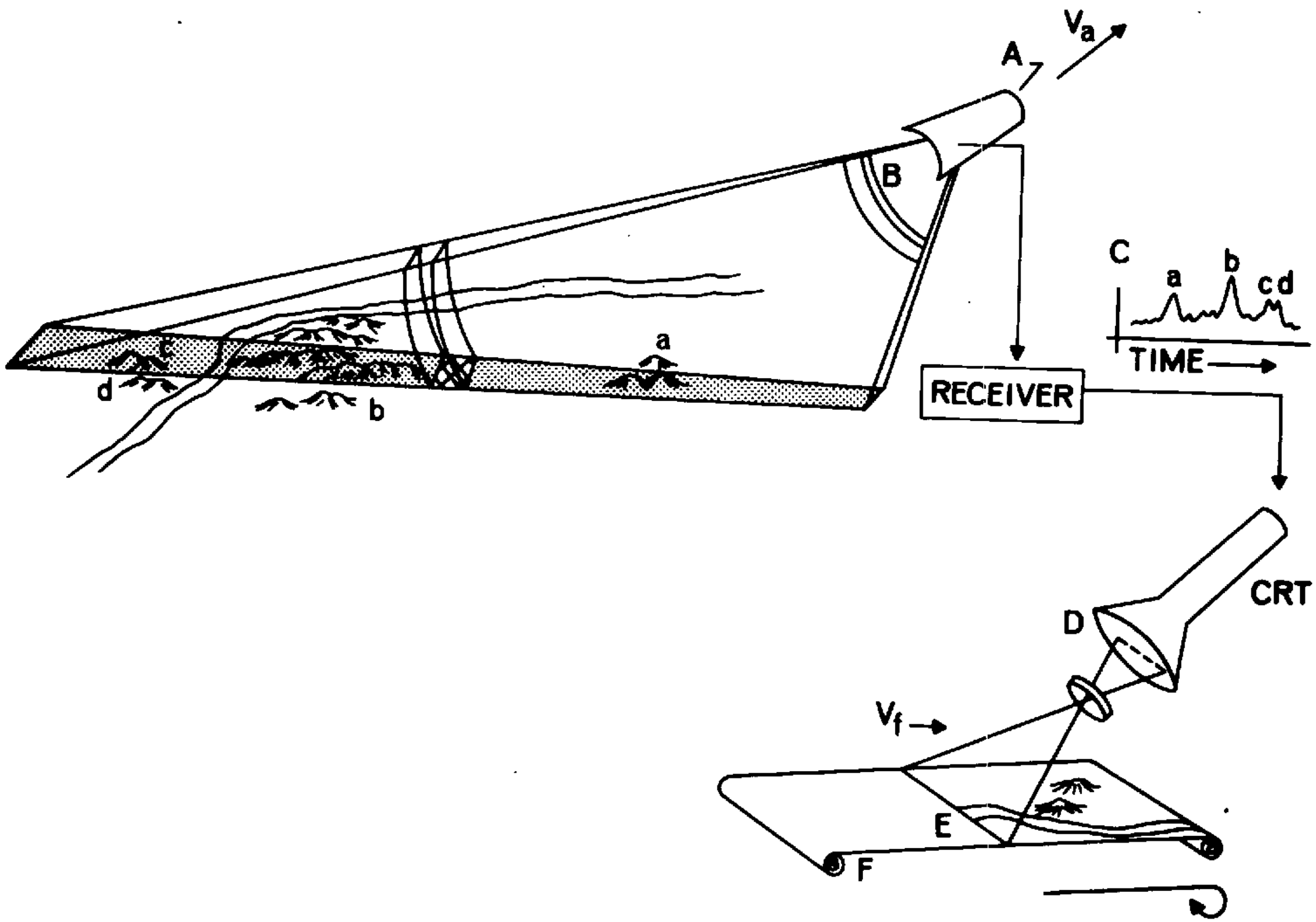


Figure 1. Sketch diagram, typical side-looking airborne radar system (modified from Westinghouse, 1967).

for targets at (c) and (d). This energy returned from points (a), (b), (c), and (d) is amplified and converted to a video signal by the receiver; the return signal from these targets is plotted from the origin as a function of the distance from the antenna to the target. The amplitude of the signal is a function of the scattering properties of the terrain. The time/amplitude video signal (c) which is displayed on a cathode-ray tube (CRT) is then recorded as a single line (e) on photographic film (f). Successive pulses are displayed on the CRT at the same position (d), and by moving the photographic film past the CRT display line at a velocity (Vf) proportional to the velocity (va), an image of the terrain is recorded on the film (f) as a continuous strip (Westinghouse, 1967).

The amplitude of the return signal, or the brightness of the target on the photographic film is determined by surface roughness, complex dielectric constant, frequency, incidence angle and polarization (Taylor, 1959). Surface roughness is an expression of the micro-relief of the terrain. A surface with a roughness much less than a quarter of a wavelength will act as a specular reflector and will generally not return any of the transmitted signal back to the antenna, thus appearing dark on the radar image. Water surfaces, playa lakes, and other smooth surfaces behave in this manner even with respect to high frequency radar. Surfaces with a relief of one wavelength or more act as rough surfaces, reflecting the energy diffusely in many directions, thus returning a portion of the transmitted energy back to the antenna and appearing bright on the radar image. The complex dielectric constant is a terrain-related parameter that expresses the amount of incident radar energy that is reflected from a given material with given electrical properties. The frequency is a function of the transmitted signal and the frequency dependence of the terrain materials. The incidence angle is the angle forming between an impinging radar beam and a normal to a given surface. For small incidence angles, when the surface is nearly perpendicular to the radar beam the radar return approaches a maximum, the return decreasing, as the incidence angle increases and the radar beam approaches grazing. Polarization is related both to the polarization of the transmitted signal and to the depolarizing effects of the irradiated terrain. Unfortunately it is generally not feasible to identify the contribution of each of these parameters to the return signal of any given target. It is toward the understanding of one of these parameters, polarization, that this research is directed.

## POLARIZATION

Radar wavelengths range from less than a centimeter to more than a meter in the microwave region of the electromagnetic spectrum. Imagery utilized in this study was produced by the AN/APQ-97, a Ka-band radar with a wavelength in the 0.75-1.18 cm range. Because radar is generated as an electromagnetic wave, electric and magnetic field vectors which are mutually perpendicular and jointly perpendicular to the direction of propagation can be defined. Mutually perpendicular, in-phase, electric, and magnetic field vectors are represented by E and H respectively in Figure 2. Their projection upon a plane perpendicular to the direction of propagation is a straight line (Figure 3). Such a wave is said to be linearly polarized. The direction of polarization is defined by the orientation of the electric field vector, E. If we assume that the Y-Z plane in Figure 2 is parallel to the surface of the earth, the wave shown has its electric field vector oriented perpendicular to the earth's surface, and is vertically polarized. Conversely, a similar wave with its electric field vector oriented parallel to the earth's surface is an example of horizontal polarization. Radar energy used in the generation of SLAR imagery can be and generally is, generated in a linearly polarized state; both horizontally and vertically polarized signals, being capable of transmission. It should be noted that the use of the terms horizontal and vertical in describing the direction of polarization of radar waves is a carry over from the period before the use of radar as an imaging device. At that time, radar signals were generally propagated parallel to the earth's surface and the terms horizontal and vertical were applicable. However, in SLAR imaging systems, the propagating antenna scans the terrain out the side of an airplane and

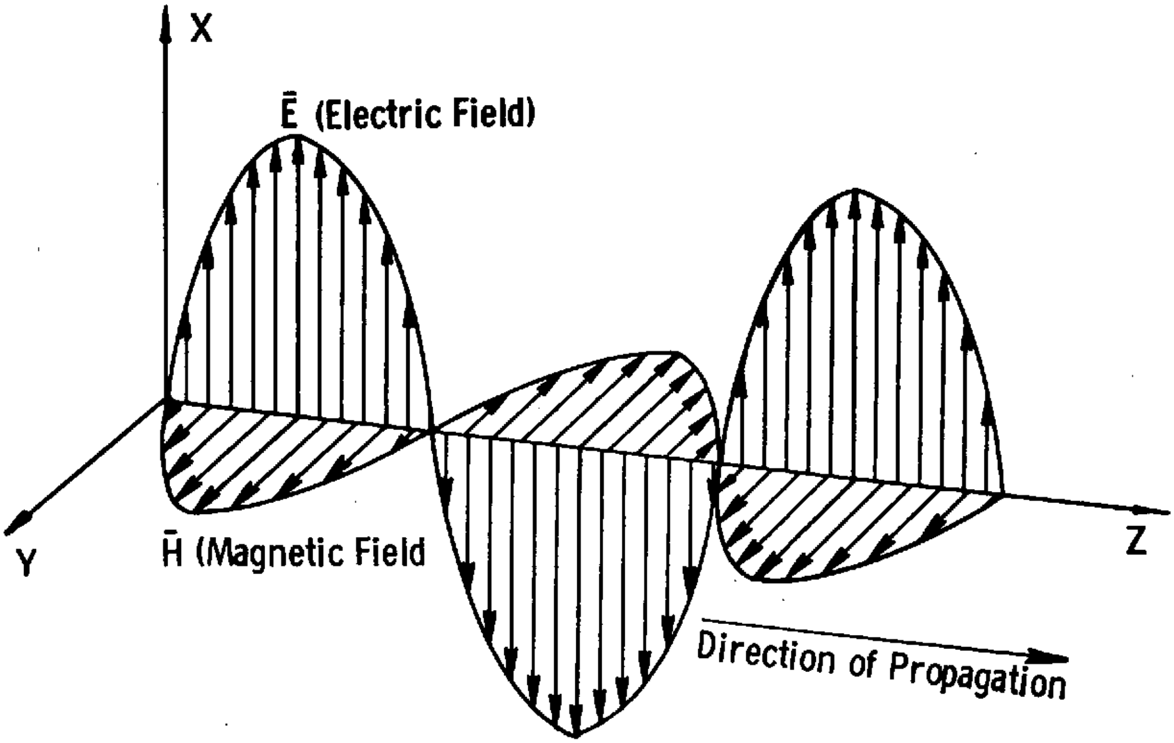


Figure 2. Electromagnetic Wave (Waite, 1972).

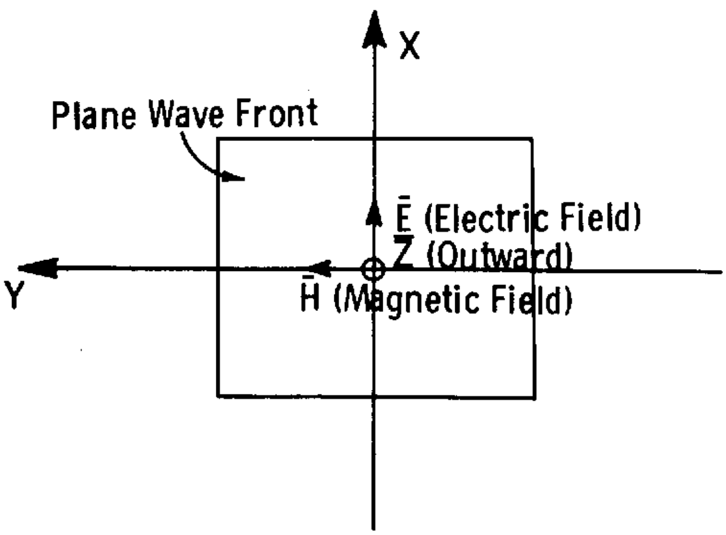


Figure 3. Plane Wave Front (Waite, 1972).

the propagation direction varies from nearly horizontal to nearly vertical, and the terms horizontal and vertical as applied to the polarization direction lose their meaning. However their use continues and their meaning is generally understood.

## MULTIPOLARIZED RADAR

In the traditional SLAR configuration the antenna polarization is horizontal, the electric vector of the radiated and received signals also being horizontal. The radar image produced by such a configuration is often referred to as being like-polarized or is designated the HH image. However, the heterogeneous nature of most earth surfaces causes the signal to be depolarized. Factors affecting the polarization of the return signal include the surface roughness and geometry of the target as well as the incidence angle and frequency of the impinging radar beam. By using a radar system with a vertically polarized antenna as well as the traditional horizontally polarized antenna it became possible to irradiate a target with either polarization and to simultaneously receive the returning echoes with both polarizations. This is the mode of operation for multipolarized SLAR systems such as the Westinghouse AN/APQ-97 and is illustrated in Figure 4. Thus, if energy was transmitted from the vertically polarized antenna, the radiated radar energy would also be vertically polarized. However the returning signal may have both vertical and horizontal components due to the factors affecting the polarization as mentioned above. By receiving the returning echo with vertically polarized and horizontally polarized antennas both the like (vertical) and the cross (horizontal) components of the returning signal can be recorded simultaneously in the form of like (VV) and cross (VH) polarized images. Likewise, by transmitting in the horizontal mode, the corresponding like (HH) and cross (HV) images can be recorded. The like and cross images of either polarization are not only simultaneously produced, but are also congruent. Thus the two images represent records taken at the same instant in time over the same area. The AN/APQ-97 format

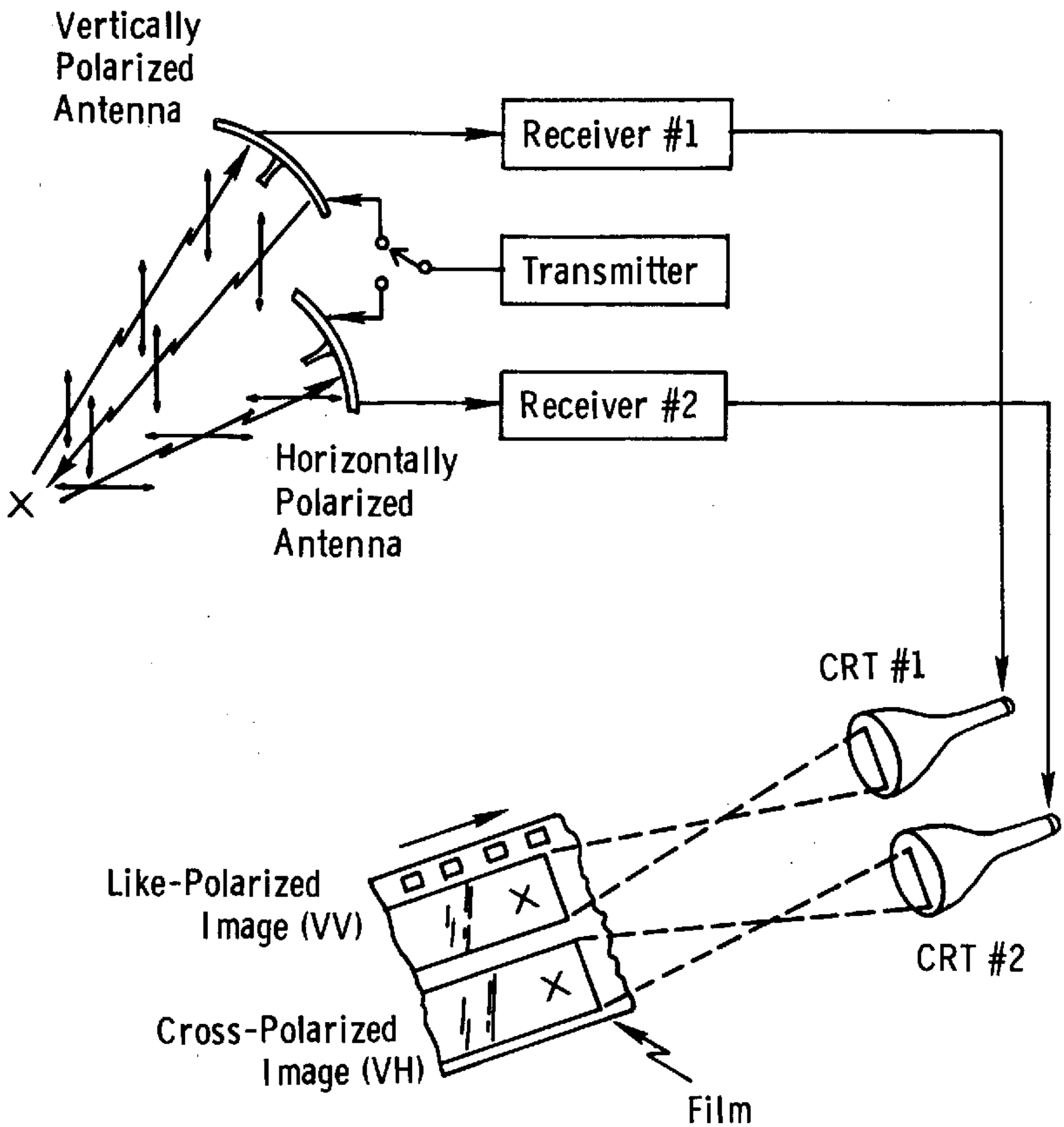


Figure 4. Simple Schematic Diagram of a Multipolarized Side-Looking-Airborne-Radar System. (Modified from Westinghouse, 1967).

consists of the two image strips displayed side by side on a continuous strip of film. When the imagery used in this study is viewed with the radar look direction toward the viewer, the like polarized image appears on top with the cross-polarized image directly below.

As a rule, the cross-polarized signal is less than the like signal. Therefore, the gain of the cross-polarized receiver must be increased to give like- and cross-polarized images of the same gray scale intensity. The lack of calibration negates the quantitative evaluation of the two images.

## PREVIOUS WORK

Simultaneously produced like- and cross-polarized images were first evaluated geologically by Dellwig and Moore (1966) for the Pisgah Crater area of Southern California. The area, a NASA test site, was imaged in 1965 with the AN/APQ-97 SLAR system using its full polarization capacity from several look directions. Geologically, the area is composed of Quaternary basalt flows, a playa, and large areas of alluvial fans. Studies of the imagery revealed that whereas the flows associated with Pisgah Crater and the areas of alluvium retained much the same appearance on all images regardless of polarization the other basalt flow (Sunshine Flow) produced returns that were distinctly darker on cross-polarized images than on like-polarized images. This reversal in tone of the Sunshine flow allowed the easy discrimination of adjacent rock types on cross-polarized images. These and other polarization-related differences lead the authors to state that "In simultaneously produced like- and cross-polarized imagery, as exemplified by the Pisgah Crater area, the geologist finds information previously unattainable from only like-polarized radar imagery," (Dellwig and Moore, 1966, p. 3601).

At about the same time as Dellwig and Moore's study, Cooper of the U. S. Geological Survey conducted a preliminary evaluation of K-band multipolarized imagery in the Twin Buttes mining district of southeastern Arizona. Revealed were two areas of low return on the HV (Cross-) image that were not isolated on the HH (Like-) image and on aerial photographs. Subsequent field investigation by Cooper established these areas as being previously unmapped outcrops of pyroxene rhyodacite. Noting no important differences in surface roughness between the outcrops and surrounding areas of alluvium, Cooper suggested the high glass content of the rhyodacite as a possible cause for the anomalous radar return. In support of his hypothesis, Cooper pointed out similar polarization differences for previously mapped outcrops in the area which were also glass-rich. He also noted outcrops of olivine-pyroxene-andesite which were low in glass content and which appeared only slightly darker on the cross-polarized image. Cooper proposed evaluation of the glass hypothesis in other areas containing glassy igneous rocks.

Gillerman (1967), following the suggestion of Cooper, tested the glass hypothesis by searching the K-band imagery of the Western United States for areas with lower return (darker) on the cross-polarized image than on the like polarized image. A number of such areas were identified, all outcrops of Tertiary or Quaternary volcanic rocks with compositions ranging from basalt to rhyolite. Field investigations by Gillerman as well as studies of collected samples showed that the glass content of the rocks involved was widely ranging, including rocks with no significant glass as well as rocks composed wholly of glass. Gillerman concluded that, "while the glass content may be a contributary factor, it is not the determining factor that accounts for a lower radar return on cross-polarized imagery than on like-polarized imagery of some rock bodies." He also pointed out such factors as roughness, topography, vegetation and rock composition as possibly being important and noted the need for further study.

## METHODS OF STUDY

This investigation was not initiated to test any single hypothesis but rather to consider all possible terrain factors that could produce the observed anomalous returns. Imagery of many different targets with similar multipolarized radar signatures was required. It was deemed necessary to examine these targets in the field as well as in the imagery interpretation laboratory. With these guidelines in mind, the following methods of study were utilized.

(a) Radar Search. The Remote Sensing Laboratory of the Center for Research, Inc., at the University of Kansas has a substantial imagery library including extensive coverage of the United States by AN/APQ-97 multipolarized radar imagery acquired in 1965 and 1966 as part of NASA'a Earth Resources Program. This imagery was searched for polarization anomalies, with the most intensive search being conducted the more arid part of the western United States. Because of the generally drier climate in this part of the country, soil and vegetation cover are limited, thus providing more areas of rock outcrop.

Anomalies were searched for visually by comparing the like- and cross-polarized images. Only those polarization differences that appeared related to rock outcroppings were considered. Cultivated areas known to produce anomalous signatures on cross-polarized imagery related to crop type and certain agricultural practices were eliminated as were areas in which soil moisture was believed to be the factor capable of producing the tonal reversal. The anomalies dealt with in this investigation are in general associated with areas of minimal vegetation cover and soil moisture content and thus require a different explanation.

(b) Documentation. Maps and other literature concerning areas that show tonal reversals were studied to determine the lithologies and general surface characteristics of exposed rocks, and also to uncover any other information that may help explain the observed radar return.

(c) Multi-sensor studies. Air photo coverage of many areas in question were studied. Other types of remote sensor data that were readily available and which covered areas of interest were utilized. Sensor products that were used included infrared imagery, oblique photography, and multiband photography.

(d) Field Check. As many of the areas as possible were visited in the field. Vegetation cover, soil condition, surface roughness and other characteristics of the terrain that might influence radar return were noted. Outcrops were investigated and samples were collected; weathering characteristics, bedding attitudes, internal structures, etc. were recorded. Because the field investigation was not simultaneous with the procurement of the imagery, it was recognized that some changes, both natural and artificial, may have occurred during the interim. Furthermore, seasonal variation in vegetated areas may be of importance. Where such differences were deemed significant in the interpretation of the imagery they were treated accordingly.

(e) Model Studies. Because of the complex nature of most earth surfaces, simplified theoretical models have been devised to quantitatively describe radar return from the ground. The results of such studies were used as guides in the field, particularly in the consideration of surface configuration.

By considering all possible factors relating to energy-terrain interaction, it was anticipated that certain consistencies would appear that would provide an explanation for the anomalous radar returns. As will be seen, this anticipation was realized.

CHAPTER 2

# PRELIMINARY STUDIES

When this study was begun, there were a few general statements that could be made concerning anomalous rock related returns on multipolarized imagery. Radar imagery of the Pisgah Crater and Twin Buttes test sites described by Dellwig and Moore (1966) and Cooper (1966) respectively contained polarization anomalies associated with volcanic rocks. Additional areas of anomalous return uncovered and described by Gillerman were also volcanic. These findings pointed to an apparent association between the volcanic nature of the rocks and their anomalous behavior on multipolarized radar imagery. Gillerman also showed that the anomalies were consistently areas that appeared bright on like-polarized images but which became dark relative to adjacent rocks on cross-polarized images.

The implication that some volcanic property was responsible for differential depolarization was almost inescapable at this point. This implication was reinforced as the search of radar imagery was undertaken and additional anomalous returns were uncovered, all associated with volcanic rocks. The early hypotheses considered were in fact based on this observed association.

The glass hypothesis of Cooper had been evaluated by Gillerman, and although little supporting evidence was found, it was re-evaluated in this study. In addition, other composition variables were considered as possible controlling factors.

The polarization effects of optically anisotropic crystals upon transmitted light are well known and are basic to the study of optical crystallography. Because of the polarized state of radar, consideration was also given to possible anisotropic properties of volcanic rocks that could cause preferential reflection and transmission of radar energy with respect to polarization orientation. The most apparent anisotropic properties of volcanic rocks would be those related to flow structure.

Crystal orientation, vesicle alignment and other internal indicators of flow direction were subject to evaluation as were external indicators expressed in the surfaces of lava flows.

Finally, because of the short wavelength of Ka-band radar (approximately 0.87 cm) the return from rock material is dominated by reflection at or near the surface. In this regard, surface geometry becomes an important factor in determining the nature of the radar return. Therefore, the surface configuration of the outcrops was considered a factor worthy of evaluation.

However, even before field investigations were conducted, preliminary studies revealed that virtually none of the initial hypotheses provided the correct explanation for the observed behavior of the anomalous outcrops on multipolarized imagery. Major inconsistencies could be found to discount these hypotheses by documenting the lithologies and by analyzing the radar images without recourse to field work.

The idea that a rock's glass content was the controlling factor in producing lower returns on cross-polarized radar imagery was essentially laid to rest by Gillerman and no additional evidence was found to support it.

Overall composition of the rocks studied also showed nothing to substantiate its role as a controlling factor in producing anomalous returns. The various rock types involved represent a fairly complete spectrum of compositions commonly encountered in volcanic rocks. Included are: rhyolite (Mono Craters, California); rhyodacite (Twin Buttes, Arizona); dacite (Three Sisters, Oregon); andesite (Twin Buttes, Arizona); and basalt (Pisgah Crater, California).

Although it appeared that the tonal reversal was associated only with volcanic rocks, it was, by no means common to all volcanic rocks. Dellwig and Moore (1966) demonstrated this in their investigation of the Pisgah Crater imagery in that of two basalt flows of similar age in the study area only one showed a significant reversal in tone on cross-polarized imagery.

Attempts to link polarization anomalies with flow phenomena of volcanic rocks were frustrated by major inconsistencies also. Tonal reversals produced by these rocks were apparent throughout the areas of outcrop and showed no allignment parallel to presumed flow directions as anticipated. The rhyolitic domes of the Mono-Inyo Craters area of California and the dacite domes in the Three Sisters area of Oregon are eruptions of viscous lavas from relatively small orifices. The most nearly circular domes are often centered directly over this orifice and as a result possess centrifugal directions of flow. Yet multipolarized radar images of these domes show widespread tonal reversals and not the diametrical pattern one would expect if flow phenomena were the causative factors.

Additional arguments against the role of flow structure is found in the imagery of the Pisgah Crater and Mono Craters test sites. In these areas, the full polarization capability of the AN/APQ-97 SLAR system was employed in numerous overflights with several different look directions. Comparison of the resulting images that share the same look-direction but which employ transmitted signals of differing polarization directions reveals that the strength of tonal reversal is independent of the transmitted polarization. That is, the tonal differences between the HH (like) and HV (cross) images are equal to those differences existing between the VV (like) and VH (cross) images and in all cases, the like images (HH and VV) appear brighter than the cross images (HV and VH).

Conversely, those flights in the two areas which share the same polarization mode but which incorporate different look directions also produce low returns on the cross-polarized image. Outcrops that have a directionally consistent slope however will produce radar returns that vary in magnitude with respect to look direction. As a general rule, when the radar looks in the direction opposite to that of the outcrop slope, the radar return will be greater than when the look and slope directions are the same. Although the strength of the return from sloping anomalous outcrops is dependent on look-direction, tonal reversal is not. The Sunshine flow at the Pisgah Crater test site and some of the flows associated with the Mono Craters possess definite slopes and as a result their radar returns are sensitive to the look-direction of the radar; however, the decrease in return on the cross-polarized image is omnipresent. Those outcrops that show essentially no dip such as the northernmost of the Inyo Craters produce radar returns which are independent of look-direction and tonal reversals which are equally contrasting on all images.

The factor causing differential depolarization appears to be persistent throughout any individual outcrop area. In addition it produces anomalous radar returns independent of transmitted polarization and look direction. Thus the factor does not appear to be anisotropic and seemingly bears no relation to flow direction or any other anisotropic character of volcanic rocks; yet, while appearing isotropic and evenly distributed throughout the outcrop, the causative factor operates independently of the composition and the glass content of the rocks as well.

Thus of the initial hypothesis considered involving: glass content, composition, flow structure, and surface configuration, only surface configuration remained as a possible cause of differential depolarization that did not arouse strong doubts during preliminary testing. The details of the terrain that are important in determining the nature of short wavelength radar return normally cannot be inferred from aerial photographs and are seldom described in published reports, and even in cases where the terrain features are well documented, the interaction of the radar pulse and the earth materials involved may be so complex and little understood as to defy description. Only by field investigation could the hypothesis concerning surface configuration be adequately tested.

Although this hypothesis could not be adequately tested in the imagery interpretation laboratory certain aspects could be questioned. One major unknown concerning the role of surface configuration was the exact mechanism by which bright like-polarized and dark cross-polarized radar returns were produced. The question also arose that if surface configuration is the determining factor in producing polarization anomalies, of what significance is the apparent association of such anomalies with volcanic rocks? Why are not all volcanic rocks capable of producing similar returns and why are outcrops of other rock-types apparently incapable of doing so?

Continued search of multipolarized imagery uncovered additional reversals that challenged the significance of the association of polarization anomalies with volcanic rocks. These reversals were produced by sandstone outcrops in a number of areas of the southwest.

CHAPTER 3

# RESULTS OF FIELD INVESTIGATIONS

## MONO AND INYO CRATERS

The Mono Craters and their southward extension, the Inyo Craters, are a chain of extinct rhyolitic volcanoes in east-central California. Intensive radar coverage of this area incorporates three orthogonal look directions and the full polarization capability. Tonal reversals are present on all passes and are associated with massive rhyolitic flows and domes (Figure II A, C, D, E, F, and G).

Field investigation revealed that areas producing anomalous cross-polarized returns differ strikingly from surrounding areas. In every case, these anomalous returns are associated with extremely blocky rhyolitic flows and domes. Individual blocks are angular to subangular with planar faces and sharp edges and range in size up to a few meters in diameter. Compositionally, the blocks vary from dense black obsidian to lightweight pumice, both rock types being equally present in any given flow and each capable of producing anomalously low cross-polarized returns. The surface of flow A is essentially devoid of vegetation, quite hummocky, and littered with angular blocks of pumice. In other parts of this flow, particularly at lower elevations, obsidian becomes more important, forming blocks composed of alternating bands of obsidian and pumice as well as blocks that are totally obsidian.

Flow A is superimposed on an older and more extensive flow, the Northwest Coulee which does not produce prominent tonal reversals. The surface of this flow (Figure II-B) is quite hummocky like flow A, however the actual surface of this flow is buried beneath a layer of ash and lapilli ejected during the initial stages of the eruption of the younger volcano. The lapilli are largely pumiceous, unconsolidated and quite variable in size, ranging from sand size particles to boulders, with fragments of obsidian being quite numerous. Unlike the fresh blocky surfaces of the younger flows, areas covered by lapilli are capable of

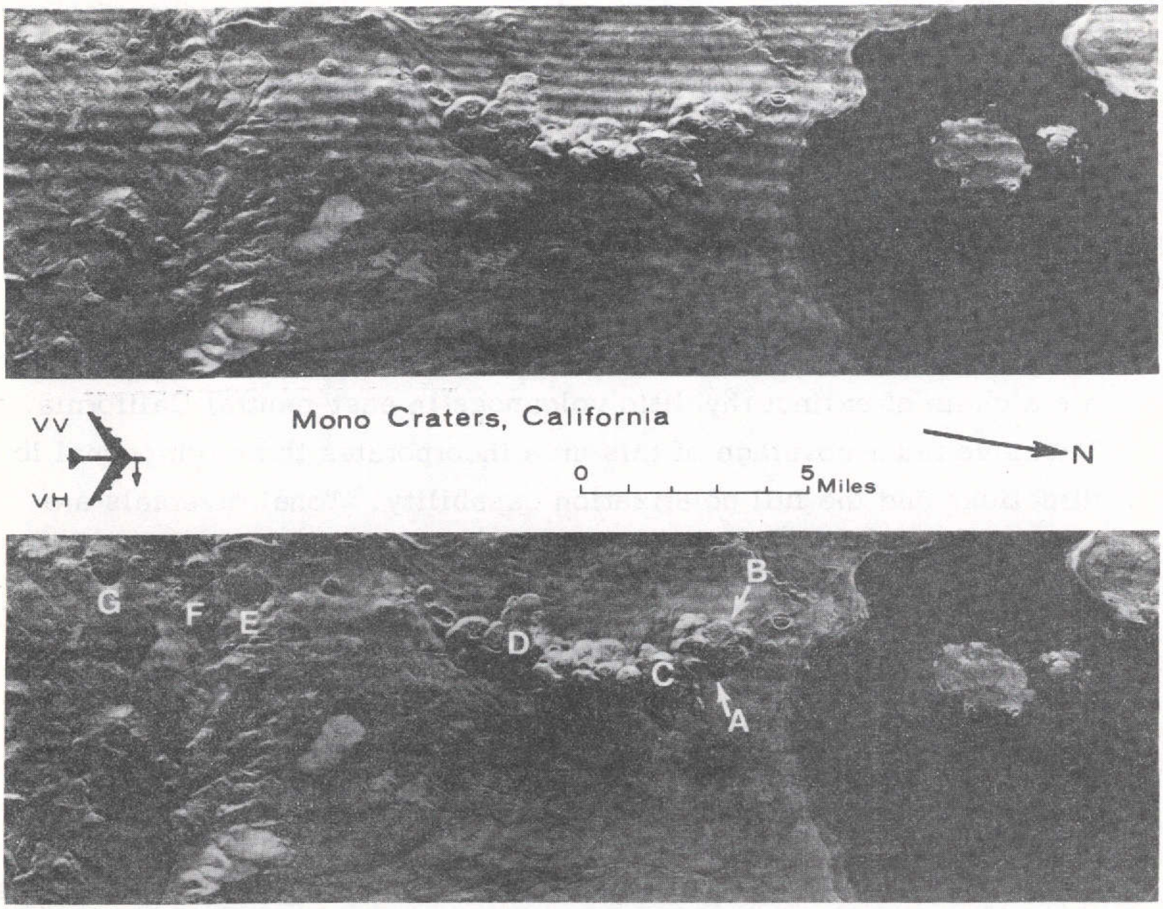


Figure I-1. Like (VV) and cross-polarized (VH) radar imagery of Mono and Inyo Craters in Mono County, California. A is a younger lava flow situated on B, the Northwest Coulee. C is the North Coulee. D is the South Coulee and E, F, and G are lava domes of the Inyo Craters.

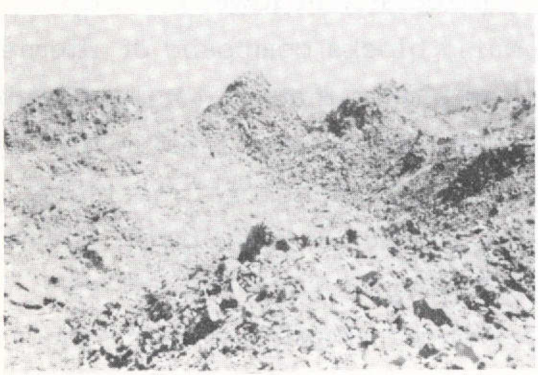

Figure I-2. Surface of flow A.

Figure I-3. Surface of flow B — the Northwest Coulee.

Plate I

maintaining a substantial cover of vegetation dominated by low shrubs. Unlike the Northwest Coulee where the ejectamenta is thin, the center of the Mono Craters is dominated by huge rounded hills resulting from thick accumulations of ash and lapilli. Both areas produce high returns on both like- and cross-polarized images.

To the south of the Mono Craters are the Inyo Craters. These are youthful, extremely blocky flows similar to Flow A except that the blocks of lava are predominately obsidian. Despite the difference in dominant lithology between the two areas, their appearance on multipolarized imagery is the same, i.e., tonally reversed, dark cross-polarized images.

## S. P. LAVA FLOW

Radar imagery of the San Francisco volcanic field in north-central Arizona (Figure II-1) contains a strong tonal reversal produced by a recent lava flow associated with a perfectly symmetrical cinder cone, S. P. Mountain. The flow is a blocky lava made up of dense fine grained basalt, finely visicular and porphyritic in texture, containing phenocrysts of plagioclase feldspar and olivine.

The surface of the flow is sparsely vegetated and very irregular being composed of polyhedral blocks of basalt one to three feet in diameter (Figure II-2). Most blocks possess smooth faces and sharp well-defined edges (Figure II-3). This type of lava makes up the entire flow. In contrast, S. P. Mountain, which was apparently formed after the eruption of the lava is composed of cinder and ash which supports a meager stand of shrubs and low trees and give no anomalous cross-polarized return. Areas surrounding the flow are largely ash covered in the vicinity of cinder cones but exhibit well developed soils elsewhere; both substrates support a sparse sod of short-stemmed grasses and maintain the same appearance on like- and cross-polarized radar.

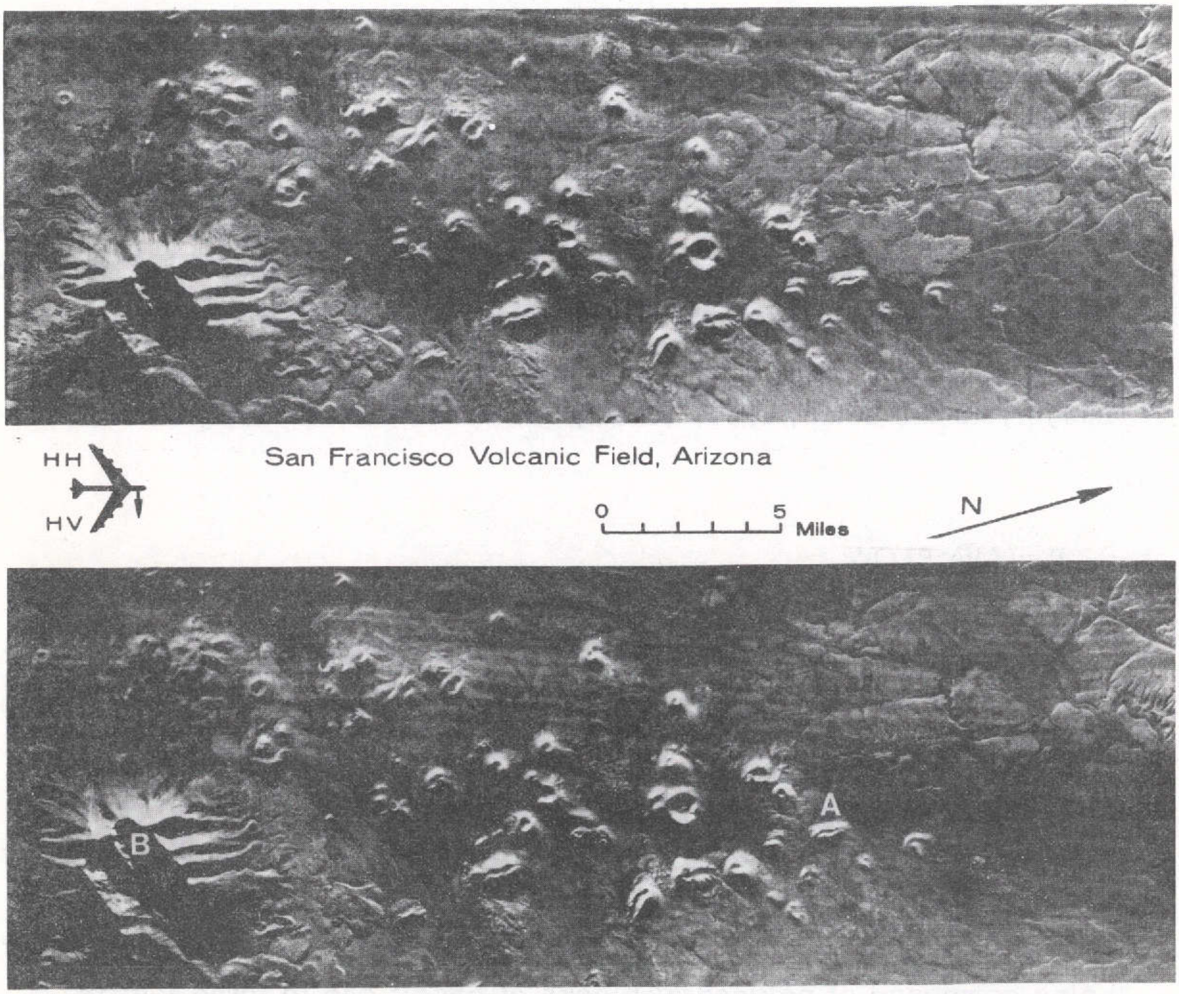


Figure II-1. Like (HH) and cross-polarized (HV) radar imagery of part of the San Francisco volcanic field in Coconino County, Arizona. A is the S.P. lava flow. B is Humphrey's Peak.

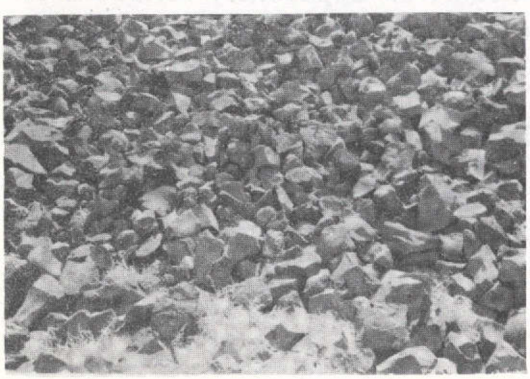

Figure II-2. Surface of S.P. flow (A).

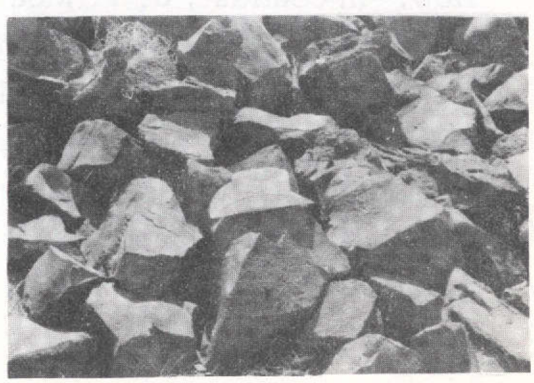

Figure II-3. Close-up of S.P. blocky basalt.

Plate II

## THREE SISTERS REGION

The Three Sisters Region of the Oregon Cascades contains a number of areas which produce distinctly lower cross-polarized returns. Figure III-1 was recorded with a westward look direction, the three peaks in the near range being the Three Sisters. Storms in the area during the overflight caused the diffuse reflections on the like-polarized image. Two separate areas of tonal reversals are present on the image, one to the south of the South Sister and a large irregularly shaped area to the north of the North Sister. These areas are in similar settings, at nearly the same location with respect to range and produce similar records on multipolarized radar imagery. In addition, both are areas of youthful Quaternary lava. However the southern flow is dacite while the northern one is basalt. Despite the wide disparity in composition, field investigation revealed certain similarities between the two flows.

The area on the south flank of South Sister is Rock Mesa, one of several dacitic flows and domes in that area (another imaging pass of the Three Sisters using an easterly look direction displays these additional dacite extrusions each producing a tonal reversal comparable to that of Rock Mesa). Field investigation found these flows and domes to be quite similar to those of the Mono Craters in appearance. Their surfaces are devoid of vegetation, very hummocky and littered everywhere with angular blocks of lava (Figure III-4). As at Mono Craters, both pumice and obsidian are quite common with obsidian being dominant especially in the small domes. Throughout all the flows, spires of black obsidian rise above the general surface and are surrounded by talus composed of large glassy blocks (Figure III-5). Elsewhere blocks of obsidian, pumice, and interlayered obsidian and pumice dominate the surface and tend to form arcuate ridges that are concentric about the apparent center of eruption. The edges of these flows are very steep and mantled beneath blocky talus slopes. The faces of the obsidian-rich blocks are very smooth often capable of specularly reflecting sunlight.

Areas surrounding these recent eruptions are underlain by older volcanic formations and are for the most part heavily forested. Surrounding Rock Mesa however are treeless tracts that are mantled with

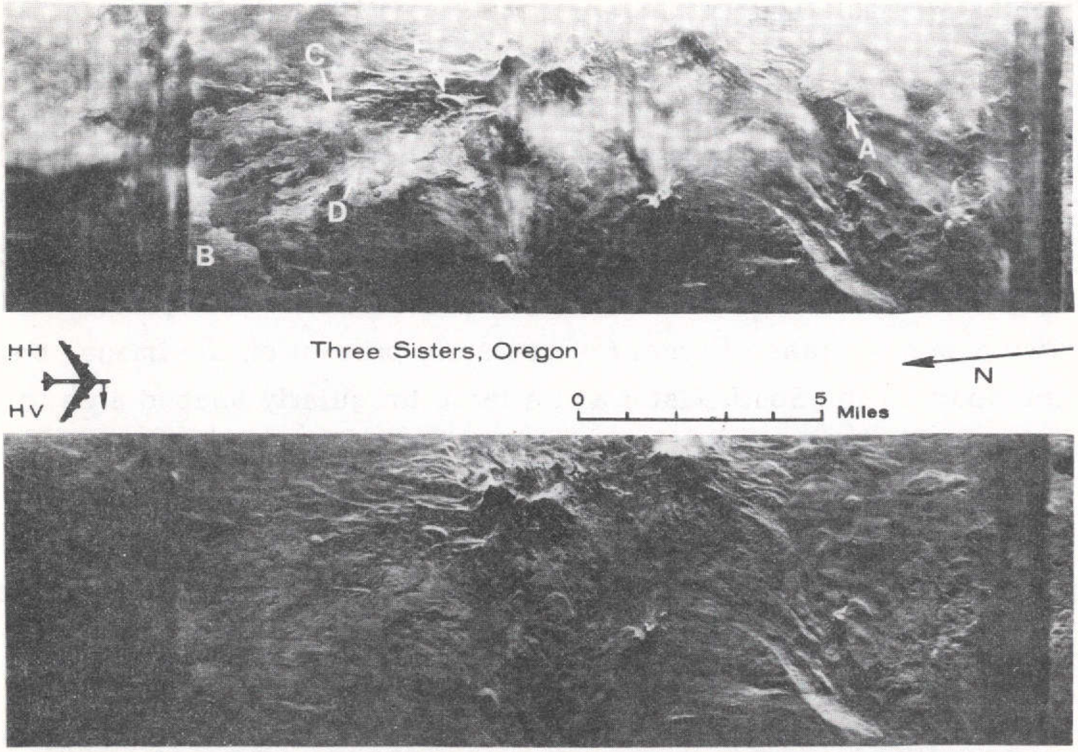


Figure III-1. Like (HH) and cross-polarized (HV) radar imagery of the Three Sisters area in Lane and Deschuttes Counties Oregon. A is Rock Mesa, a dacite lava flow. B is lava erupted from Belknap Crater (off the image) C, D, and E are Yapoah Crater. Four-in-one Cone and Collier Cone respectively, sources of coelescing lava flows to the North.

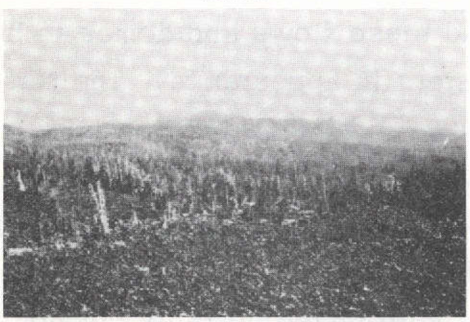

Figure III-2. Yapoah Crater basalt (C).

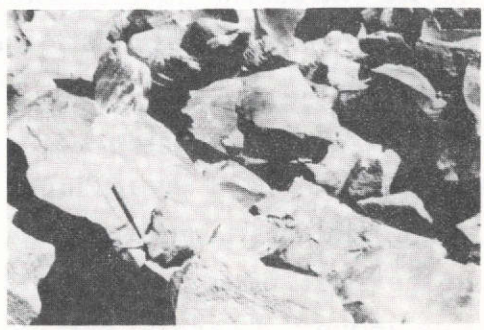

Figure III-4. Glassy Blocks of Rock Mesa dacite.

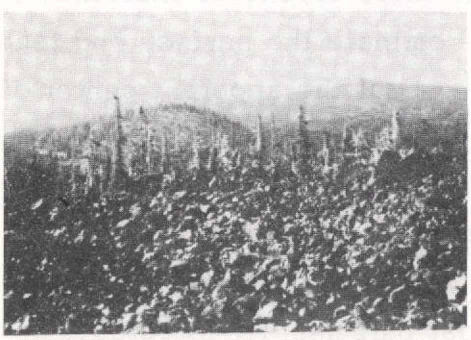

Figure III-3. Belknap Crater basalt (B).

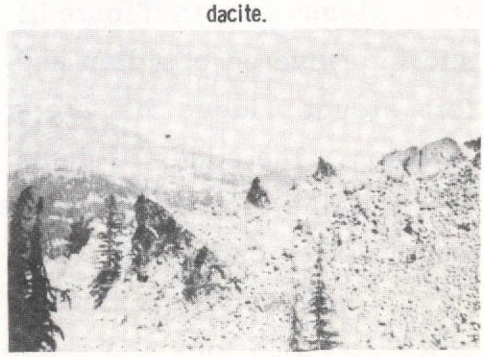

Figure III-5. Surface of dacitic lava dome.

Plate III

an accumulation of pumiceous ash probably produced during the early stages of the formation of Rock Mesa. These areas support only a meager growth of bunch grasses and produce low returns on both like- and cross-polarized images. Forested areas generally give brighter returns.

The extensive flows of basalt to the north of the North Sister which also produce tonal reversals resulted from the eruptions of several volcanoes. The larger northern-most flow is part of a large shield volcano associated with Belknap Crater lying just off the image to the left. The other lavas in this area flowed in a northwesterly direction down the slope of the North Sister being erupted from three primary sources — Yapoah Crater, Four-in-One Cone, and Collier Cone.

All those flows are similar in appearance being blocky lavas of recent origin. Vegetation is essentially lacking, limited to widely scattered coniferous trees growing in favorable locations. The blocky nature of the lava appears to be dominant throughout the flows with aa and pahoehoe being important only in local situations. Overall, the lava is similar to that found at S. P. Crater (Figure II-2) being composed of blocks 30-100 cm in diameter with plane faces and sharp edges. Some parts of these flows differ from those at S. P. Crater by being scoriaceous to varying degrees. Figure III-3 is a view toward Belknap Crater showing the extensive flows of blocky basalt responsible for the tonal reversals on the left edge of Figure III-1. Figure III-2 shows the North Sister in the background and a portion of the lava that issued from Yapoah Crater. This lava is blocky also but less scoriaceous than the Belknap lava in Figure III-3. The surfaces are quite smooth, many specularly reflecting sunlight in Figure III-2.

Areas adjacent to the anomalous flows in Figure III-1 display low return on both like- and cross-polarized images. These areas are underlain by older basalt and andesite produced by the main volcanoes of the High Cascades (Williams, 1944). However dense coniferous forests developed on these rocks dominate the return from these areas. The anomalous dark appearance of the lava flows on the cross-polarized image closely matches the returns from the surrounding forest with respect to gray level, and separation of the two is difficult. Discrimination of the recent basalt flows on the like-polarized image however is quite simple due to their high return which contrasts sharply with the low returns of the forests. In addition, numerous forested kipukas can be identified within the flows also because of contrastingly low returns.

SUNSHINE LAVA FLOW

The Pisgah Crater test site of southern California contains two Quaternary basalt flows, outcrops of older volcanics, a playa, and extensive areas of alluvium. Since multipolarized imaging in November of 1965, the area has been of interest because of the disparity in cross-polarized return existing between the two basalt flows. Six passes were flown with five different look directions using both horizontally and vertically transmitted signals. On all passes, the Pisgah lavas produce similar returns on both like- and cross-polarized images whereas the Sunshine lavas are distinctly darker on all cross-polarized images.

In Figure IV-1 are HH and HV images of the Pisgah Crater test site showing the Pisgah flows (A), Lavic Lake (B), and the Sunshine Flows (C). On the HV image, the Sunshine Flows appear much darker when compared with the HH image and can be easily distinguished from the surrounding alluvium which maintains bright return on both the HH and HV images.

Wise (1966) in mapping the Pisgah and Sunshine lavas, divided the Pisgah field into three distinct flows which he separated on the basis of the phenocryst minerals: the first eruption, a microporphyritic alkali - olivine basalt; the second, a porphyritic olivine basalt largely aa in nature; and the final eruption, a porphyritic olivine basalt which is pahoehoe over its entire surface. He similarly divided the Sunshine field into two flows both being porphyritic alkali-olivine basalt. Wise believes the Sunshine eruption occurred first followed by the first eruptive phase of the Pisgah field, then the second Sunshine flow, and then the final two Pisgah flows. Thus not only are the two fields quite similar lithologically, but also appear to overlap in age.

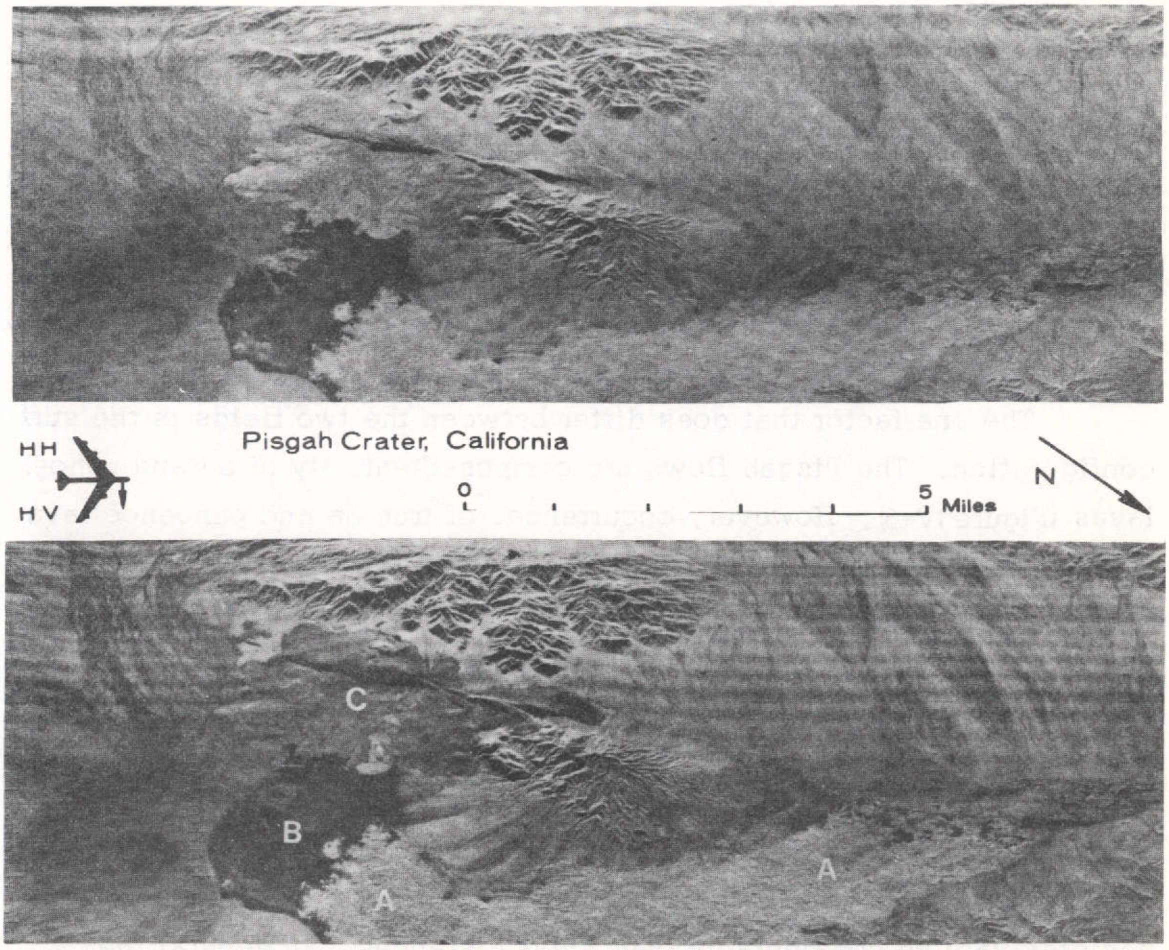


Figure IV-1. Like (HH) and cross-polarized (HV) radar imagery of the Pisgah Crater area, San Bernardino County, California. A is the Pisgah flows, B is Lavic Lake, C is the Sunshine flows.

Figure IV-2. Blocky lava of Sunshine flows (B).

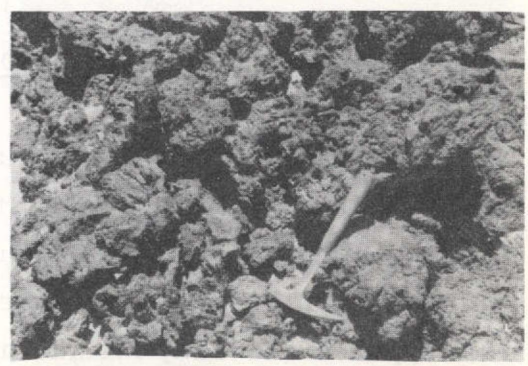

Figure IV-3. Aa lava of Pisgah flows (A).

Plate IV

In addition, there is little difference between the two flows in the extent of weathering and both support the same, extremely sparse, vegetation. In general, the Sunshine flows exhibit more relief, occupying steep slopes in places. However, this appears to be of little significance since gently sloping surfaces of the Sunshine flows that are comparable to the dominant terrain on the Pisgah flows produce tonal reversals similar to those on steep slopes. Orientation of slopes is not a factor either since tonal reversals occur independently of look-direction and location in range.

The one factor that does differ between the two fields is the surface configuration. The Pisgah flows are composed entirely of aa and pahoehoe lavas (Figure IV-3). However, occurrences of true aa and pahoehoe lava in the Sunshine field are very limited. Instead the lava is predominantly of the blocky variety. Figure IV-2 is a view of the Sunshine lavas. The surface of the flow presents a rolling topography composed of many small closely spaced hills that are made up of shattered blocks of basalt. Blocky fragments also litter the surfaces between the hillocks. Individual blocks range in size from 50 cm in diameter downward with the larger blocks being found in association with the low hills.

The basalt is of a vesicular nature with the size and number of vesicles varying considerably over short distances. In general the vesicles are larger and more widely spaced than those of either aa or pahoehoe. As a result the lava of the Sunshine field is denser than that of the Pisgah field.

## MALPAIS LAVA FLOW - CADY MOUNTAINS AREA

Additional tonal reversals are present on an imaging strip recorded near the Pisgah Crater test site. One such reversal is produced by the Malpais lava flow (A, Figure V-1) located in the Rodman Mountains to the west of Pisgah Crater, the other reversal is produced by various rock types in the Cady Mountains (B, Figure V-1) located north of Pisgah Crater.

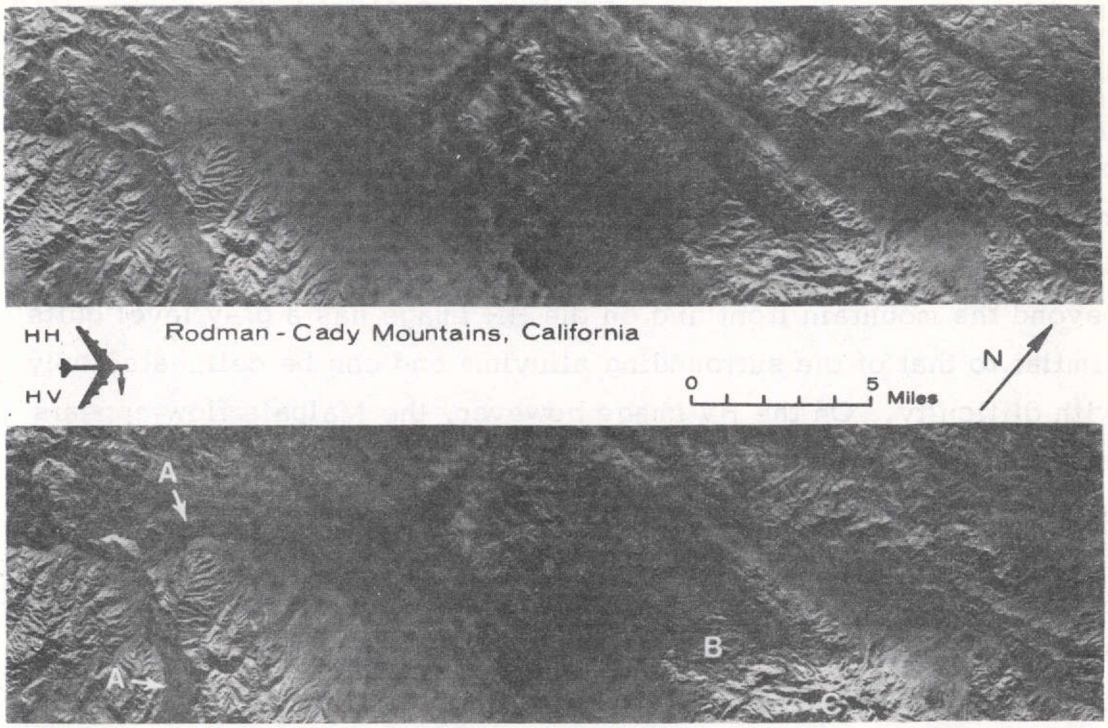


Figure V-1 Like (HH) and cross-polarized (HV) radar imagery of the Rodman and Cady Mountains area, San Bernardino County, California. A is the Malpais flow. B is volcanic formations in the Cady Mountains. C is granitic outcrops.

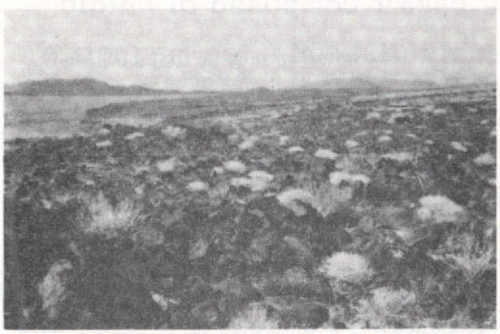

Figure V-2. Surface of Malpais flow (A).

Figure V-4. Surface of andesite-breccia outcrop (B).

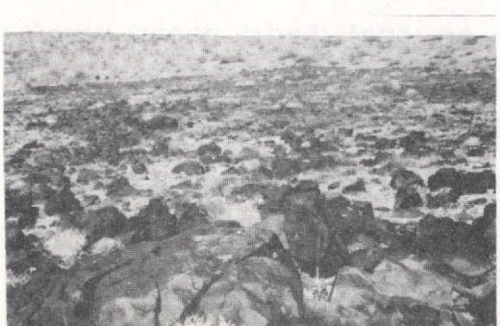

Figure V-3. Close-up of Malpais blocky basalt.

Figure V-5. Close-up of andesite-breccia.

Plate V

The HH and HV images in Figure V-1 were recorded with a southeast look direction. The Malpais flow lies in the far range and extends to the mid-range being erupted from Malpais Crater which lies off the image to the southeast. That portion of the flow located in the mountains can be delineated on either polarization due to the striking difference in topography. The extreme end of the flow however, lies beyond the mountain front and on the HH image has a gray level quite similar to that of the surrounding alluvium and can be delineated only with difficulty. On the HV image however, the Malpais flow appears much darker, contrasting with the alluvium which maintains the same relative gray level.

Various portions of the flow appear on two additional image passes which were recorded with vertically transmitted signals, southwest and northeast look-directions, and near and far range locations. Despite these varying parameters, the Malpais flow displays the same radar return, producing darker cross-polarized images.

Dibblee and Bassett (1966) describe the Malpais flow as a "black, hard, vesicular microcrystalline basalt composed of calcic plagioclase laths, pyroxene, olivine, finely disseminated magnetite, and very small phenocrysts of olivine and labrodorite."

The surface of the Malpais flow (Figures V-2 and V-3) is quite rough and supports a meager growth of low shrubs and grasses. The lava is quite similar to the nearby Sunshine lava in being a blocky basalt. The individual blocks are generally polyhedral averaging about 50 cm in diameter. The Malpais basalt is vesicular with the size and number of vesicles being quite variable across the surface of the flow. In addition, most exposed rock surfaces are coated with desert varnish which tends to reduce the micro-roughness of the block faces.

Rocks adjacent to the Malpais flow include Quaternary alluvial fan gravels, older Quaternary alluvium, and Tertiary fanglomerates which possess quite similar terrain characteristics including sparse vegetation, and rough gravelly surfaces. These rocks give similar returns on both like- and cross-polarized images.

Lower cross-polarized returns on SLAR imagery of the Cady Mountains (Figure V-1) are associated with various volcanic formations including andesite, andesite breccia, basalt, basalt breccia, and volcanic fanglomerate, all Tertiary in age (Dibblee and Bassett, 1966A Due to these lower cross-polarized returns, the contact between these formations and adjacent granitic rocks is enhanced on the cross-polarized image, the granitic rocks — maintaining constant bright returns on both HH and HV images. The line of tonal contrast observec on the HV image can be closely correlated with the contact between the volcanics and granititic rocks as mapped by Dibblee and Bassett (1966.

Although the volcanic formations include basalt and andesite ar breccias and fanglomerates derived from these rock types, their surfac expressions are quite similar in being sparsely vegetated gravelly surfaces littered with angular volcanic boulders up to 1 m in diameter. Figure V-4 is a view on an exposure of andesite breccia showing the extremely rough surface dominated by angular cobble-and-boulder-size andesitic fragments. The andesite itself is dense and porphyritic; basaltic rocks composing similar blocky terrains are massive and generally finely crystalline (Dibblee and Bassett, 1966A). Figure V-5 is a close-up of the surface of the andesite-breccia showing the large angular blocks of andesite and the matrix of cobble and gravel-sized andesitic fragments. Older surfaces on the large blocks also exhibit dark coatings of desert varnish.

Adjacent outcrops of granitic rocks are mapped as granite to quartz monzonite by Dibblee and Bassett (1966A). These rocks which a bright on both like- and cross-polarized images, produce terrains whic differ markedly from those of the volcanic formation. Being coarse-grained, these rocks tend to undergo granitoid weathering forming rougl rounded outcrops mantled by accumulations of granitic sand composed of rock and mineral fragments and individual crystals.

## TWIN BUTTES AREA

Radar imagery of the Twin Buttes mining district contains a number of areas of tonal reversals occurring on the southeast flank of the Sierrita Mountains. These were uncovered by Cooper (1966). The reversals correlate with outcrops of Tertiary volcanics that occur in an L-shaped pattern extending east and south from Tinaja Peak (VI-1). All of the outcrops are topographically expressed except for the three southernmost outliers which fail to rise above the general elevation of the surrounding alluvial plain. The two smallest outcrops had been unmapped previous to Cooper's evaluation of the imagery. Cooper established all three outcrops as being pyroxene rhyodacite. Larger outcrops in the vicinity of Tinaja Peak have been mapped as hornblende biotite rhyodacite, with those lying to the east of the peak being olivine pyroxene andesite (Cooper, 1966).

As previously mentioned (page 9) Cooper in his field investigation noted little difference in surface roughness between the rhyodacite outcrops and the adjacent alluvium. Gillerman (1967) concurred with this observation but in addition, noted a vegetation difference between the two areas. As a result of subsequent field investigation, the vegetation difference has been verified, however, an important difference in surface roughness has also been noted. The outcrop surfaces are much rougher than areas of alluvium, being covered with cobble and boulder sized blocks of rhyodacite as shown in Figure VI-2. The individual blocks are roughly polyhedral similar to those found on recent blocky flows in having planar faces, however the corners and edges have been slightly rounded by weathering and older surfaces are coated by desert varnish. The surface of the alluvium on the other hand is largely sand and gravel and noticeably lacks the large boulders that dominate the outcrop surfaces; thus presenting a much smoother surface (Figure VI-3).

Vegetation differences between the two rock types can be explained by gross edaphic differences. Areas of alluvium support a mesquite savanna with an understory of short stemmed grasses which extends on to areas of outcrop. Mesquite also occurs on the rhyodacite

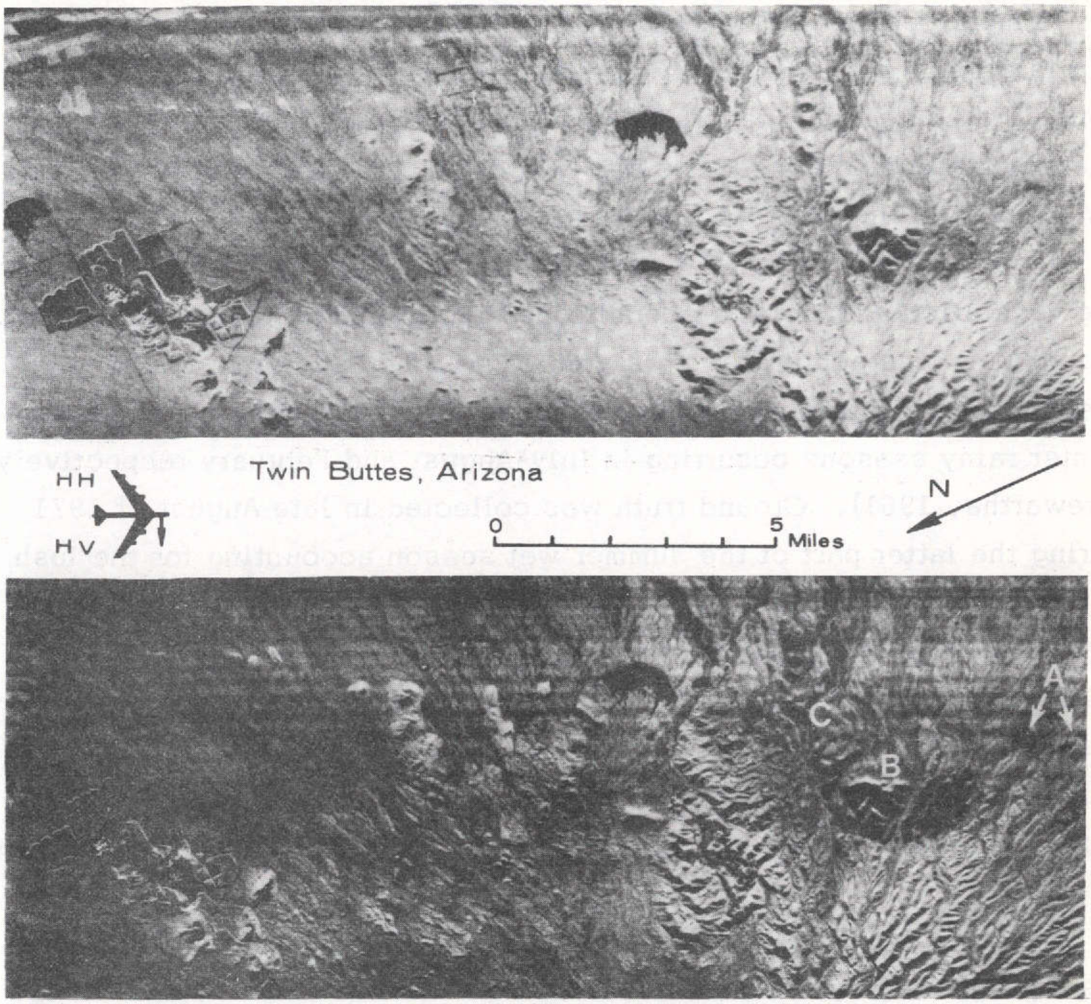


Figure VI-1. Like (HH) and cross-polarized (HV) radar imagery of the Twin Buttes area, Pima County, Arizona. A is outcrops of pyroxene rhyodacite. B is Tinaja Peak, hornblende-biotite rhyodacite, C is an outcrop of olivine-pyroxene andesite.

Figure VI-2. Surface of large pyroxene rhyodacite outcrop in area A.

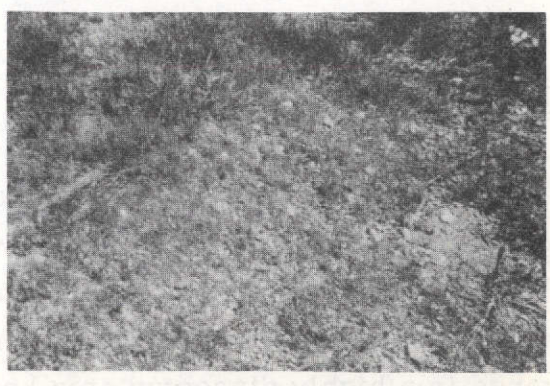

Figure VI-3. Surface of alluvium surrounding outcrops in area A.

Plate VI

but is much reduced in coverage and size, taking on a shrub-like form and is effectively replaced by stands of ocotillo. The thick, weakly consolidated alluvium favors the growth of the extensive root system characteristic of the mesquite tree while the thin extremely blocky soil on the outcrop inhibits its full development.

It is unlikely that the ground photos in Figure VI accurately portray the vegetation and moisture conditions that prevailed when the imagery in Figure VI-1 was acquired. This area of Arizona experiences a bimodal distribution of rainfall through the course of a year with summer and winter rainy seasons occurring in July-August and February respectively (Trewartha, 1961). Ground truth was collected in late August of 1971 during the latter part of the summer wet season accounting for the lush appearance of the grasses and the presence of many small ephemeral plants and flowers. The imagery was flown in early November of 1965 during the autumn dry season when the ephemerals are gone, the grasses are dry and the drought deciduous ocotillo has dropped its leaves. The winter deciduous mesquite would probably still be holding its leaves in early November, however they represent only discontinuous cover at the most.

Because of the nature of the vegetation and its dry condition at the time of imaging, radar return from both alluvium and rhyodacite as seen on the imagery in Figure VI-1 is considered to be dominated by reflection from the respective rock surfaces with the effect of vegetation being secondary.

## MECCA HILLS

Radar imagery in the Imperial Valley of Southern California contains a number of areas with lower cross-polarized return. In Figure VII-1 are the HH and HV images of the north end of the Salton Sea recorded with a southwesterly look-direction. Tonal reversals occur in the near range in a highly dissected area known as the Mecca Hills. Due to the rugged topography, radar returns on the HH image are generally very high or very low depending upon the orientation of the local terrain with

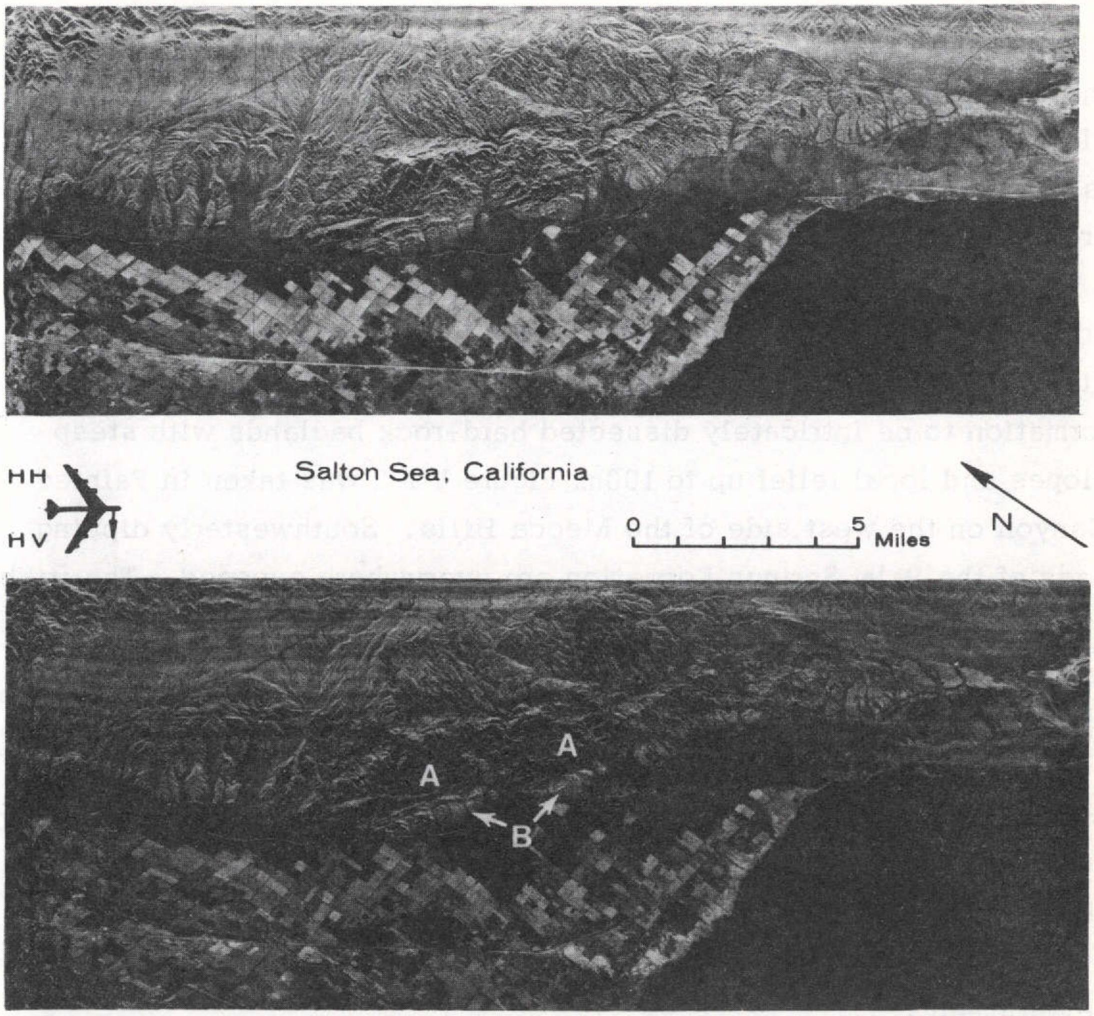


Figure VII-1. Like (HH) and cross-polarized (HV) radar imagery of the Salton Sea-Mecca Hills area of Riverside County, California. Outcrops of the Palm Springs Formation are at A, outcrops of the Ocotillo conglomerate are at B.

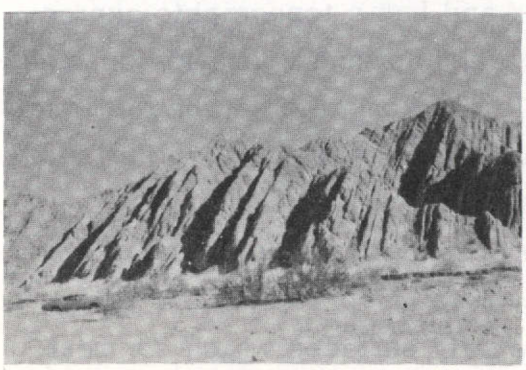

Figure VII-2. Outcrops of Palm Springs Formation (A).

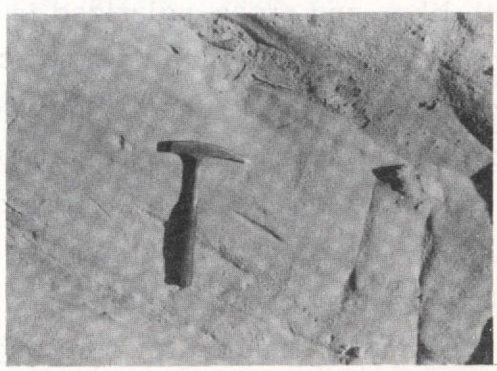

Figure VII-3. Close-up of Palm Springs Formation outcrop surface.

Plate VII

those slopes facing the aircraft giving higher returns. Comparison of the like- and cross-polarized images reveals large areas which, although responsible for bright HH return, display an HV return which is much reduced in intensity. These tonal reversals correspond to areas mapped as Palm Springs Formation by Dibblee (1954).

The Palm Springs Formation in this area is buff to pink colored arkose, fine to coarse grained and containing thin interbedded clays. Field investigation showed the anomalous outcrops of the Palm Springs formation to be intricately dissected hard-rock badlands with steep slopes and local relief up to 100m. Figure VII-2 was taken in Painted Canyon on the west side of the Mecca Hills. Southwesterly dipping beds of the Palm Springs Formation are everywhere exposed. The friable nature of the Palm Springs Formation favors granular weathering, as a result, fresh, rubble-free exposures are generally formed, surrounded by sand-choked arroyos. Figure VII-3 is a close-up of a Palm Springs outcrop showing a smooth rounded surface which is typical of the extensive exposures of the formation in this area. Effects of thin clay beds on the overall radar expression of the formation is considered negligible as is the effect of vegetation which is restricted to sparse stands in water courses and on outcrops with more favorable soil development.

The unit above the Palm Springs Formation is the Ocotillo conglomerate which forms a band of hills and ridges at the extreme western edge of the Mecca Hills. These exposures produce bright images on both like- and cross-polarized images, and has a topographic expression that appears similar to that of the Palm Springs Formation on side-looking radar. As a result, the Ocotillo conglomerate can be distinguished from the adjacent Palm Springs Formation only on the cross-polarized image on which the Palm Springs displays a lower return.

Although Ocotillo conglomerate is similar to the arkose of the Palm Springs Formation in composition, it is much coarser and is poorly consolidated, tending to form rough gravelly surfaces which contrast sharply with the smooth bare-rock outcrops of the Palm Springs Formation.

## SOUTHERN MUDDY MOUNTAINS

Multipolarized radar imagery in southern Nevada contains a number of small areas that have distinctly lower returns on the cross-polarized image. Figure VIII-1 is an image centered about 30 miles east of Las Vegas produced with southeasterly look-direction. Tonal reversals are concentrated in three areas: (A&B) the south and east sides of Pinto Valley, respectively and (C) a natural amphitheater calle the Bowl of Fire (Hoover Dam 15-minute quadrangle 1953). All these reversals fall within areas mapped as Aztec sandstone (Jurassic) by Bowyer, Pampeyan and Longwell (1958).

These areas have a speckled appearance on the like-image with bright spots on a dark background, the bright returns corresponding to slopes facing the aircraft. On the cross image, however, the areas are almost completely dark.

Field investigation correlated the anomalous returns with rugge( bare-rock outcrops of the Aztec. The numerous small bright returns on the like-images of the eastern end of Pinto Valley (A) were found to be caused by resistant sandstone outliers that protrude above surrounding alluvial debris. Large hogback ridges on the south side of Pinto Valley provide exposure of almost the full thickness of the Aztec in area (B). The Bowl of Fire (C) is encircled by sharp-crested ridges and contains large exposures of the Aztec, the bright red coloration the sandstone exhibits in this area providing the inspiration for its name.

Longwell (1928) described the sandstone that is now called the Aztec as being massive and brick red in color with abundant cross bedding. The unit is composed of medium to fine-grained quartz sand of rounded and frosted grains. Minor feldspar and other accessories are also present with iron oxide and calcium carbonate forming the cem( The actual configuration of the Aztec outcrop surfaces was found to be quite irregular. Figure VIII-2 is a westward view of one of the small Aztec outliers at the eastern end of Pinto Valley. The total lack of vegetation on the exposure is apparent as is the absence of detrital material and the lithologic homogeneity of the Aztec. True bedding

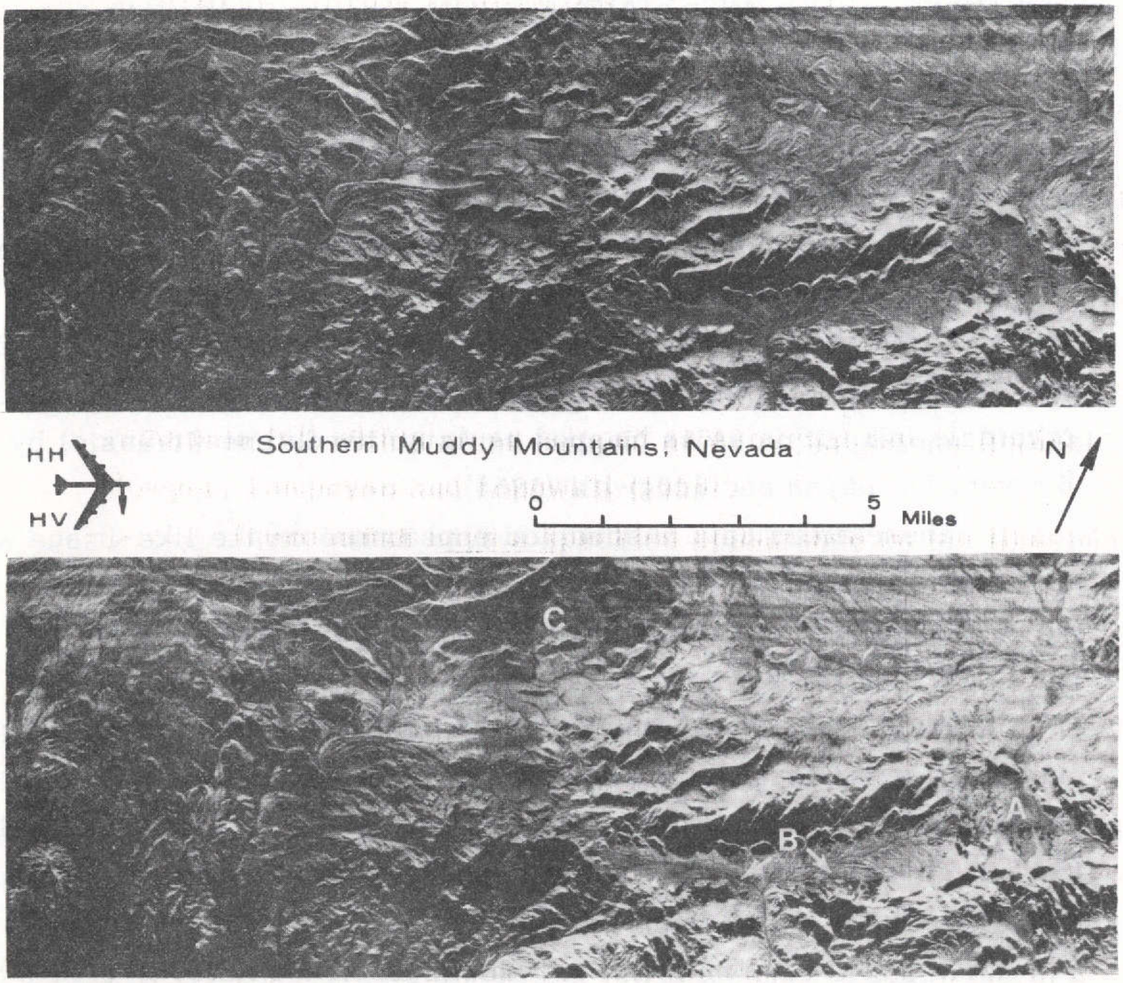


Figure VIII-1. Like (HH) and cross-polarized (HV) radar imagery of part of the Southern Muddy Mountains in Clark County, Nevada showing outcrops of the Aztec Sandstone at A and B in Pinto Valley and at C, the Bowl of Fire.

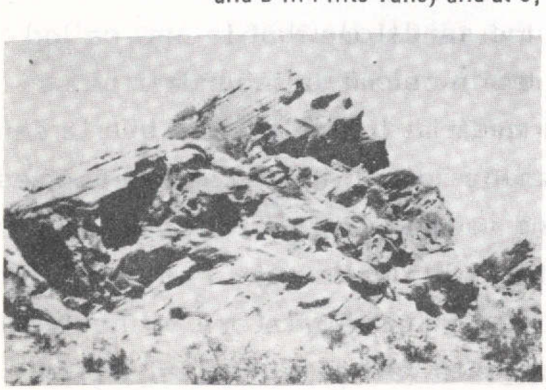

Figure VIII-2. Small Aztec Sandstone outlier in area A.

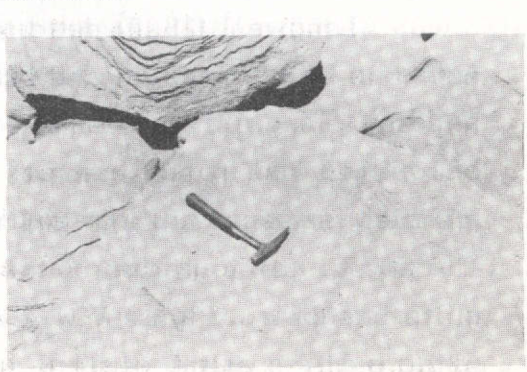

Figure VIII-3. Close-up of Aztec Sandstone outcrop surface.

Plate VIII

planes are lacking; however, large scale tangential cross bedding is omnipresent. Although the outcrop surface is quite irregular and extensively eroded it is remarkably free of rubble. Deposits of sand about the perimeter of such exposures as well as in pockets and crevices on their surfaces attest to the fact that weathering is accomplished primarily by granular disaggregation rather than separations along planes of weakness. The result of such weathering of this friable sandstone is an abundance of fresh rock surfaces (Figure VIII-3), which because of the small grain size tend to be quite smooth. This is in contrast to the surfaces of alluvial fans, an example of which occurs in the foreground of Figure VIII-2. Material compising such surfaces ranges from fine sand to boulders with gravel being most abundant. Vegetation on alluvial material is dominated by low shrubs especially creosote bush and sage which are widely spaced and provide minimal cover; Aztec outcrops are essentially devoid of vegetation, thus the radar returns from both rock types is highly dependent upon their respective surface characteristics.

## TICABOO CREEK

Multipolarized radar coverage of portions of southern Utah contain many tonal reversals, most of which can be related to outcrops of the Navajo Sandstone: An example is shown in Figure IX, a radar image of an area in the Henry Mountain Region bounded by Mount Ellsworth on the west and the Colorado River on the east, in Garfield County, Utah. In the near range is extensive canyon development along Ticaboo Creek and its tributaries. Hunt (1954, p. 62) in his study of the Henry Mountains states, "In the canyon part of the Henry Mountains region, the Navajo forms steep to vertical cliffs as much as 500 feet high. In some places the base of the overlying Carmel formation extends almost to the rim of the canyon so that the full thickness of the Navajo is in the cliffs. At other places the Carmel has been stripped back as much as 2 or 3 miles leaving the Navajo sandstone carved into an intricate maze of bare rock domes of all sizes and heights — a hard-rock badland topography." The latter is applicable to the Navajo in the Ticaboo Creek

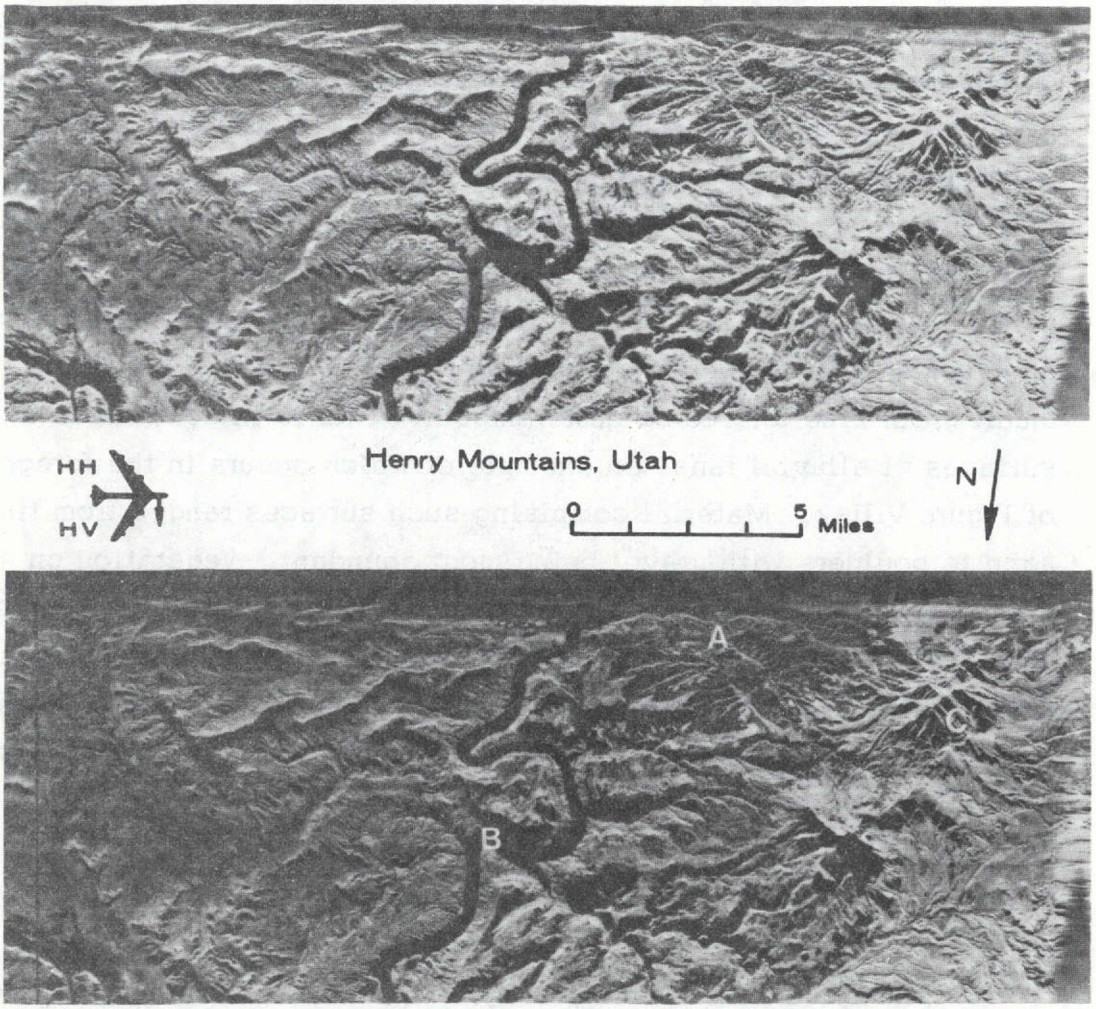


**Figure IX-2.** Like (HH) and cross-polarized (HV) radar imagery of the Ticaboo Creek area, A in Garfield County, Utah, an area of extensive Navajo Sandstone outcrops. B is the Colorado River, C is Mount Ellsworth in the Henry Mountains.



Plate IX

area. The Carmel is preserved only as the caprock of a few high-standing mesas. The Navajo dominates the surface in this highly dissected area and is expressed as a speckled return on the like-image composed of bright spots on a generally dark background. On the cross-polarized image, however, the Navajo appears almost completely black and stands out in contrast with the overlying Carmel and the underlying Kayenta sandstone which display equally bright returns on both like and cross images.

The Navajo Sandstone has been described by many authors reporting on studies in the Colorado Plateau. Lithologic descriptions generally correspond with those of the Aztec Sandstone, stressing the massive appearance, large scale cross bedding, and dominant fine-grained quartz mineralogy (Longwell, Miser et al., 1923, Gilluly and Reeside, 1927, and Hunt, 1951). In addition, reference to the grotesque shapes and picturesque yet rugged topography developed on outcrops of the Navajo is frequent. Longwell, Miser et al. (p. 13) describe exposures of Navajo Sandstone in southern Utah as forming "great tracts of almost impassable badlands, in which domes, 'mosques,' and 'minarets' are common features." Gilluly and Reeside (1927, p. 72) studying in the San Rafael Swell region of Utah state that: "Through most of this area the Navajo forms a very characteristic topography, marked by huge domes and rounded masses where the overlying rocks are soft or have been removed and by sheer cliffs many scores of feet high where they are resistent. These cliffs and domes are among the most prominent features of the country and give much of the picturesque gradeur for which plateau scenery is so famous."

The lack of vegetation and soil on the Navajo, as revealed by aerial photos and the explicit descriptions of broad bare-rock areas of the Navajo outcrop by Hunt, strongly suggest that radar return from the Navajo in these areas is determined solely by the bedrock. Examination of the Navajos outcrops on the like image reveals a high return from those surfaces that are inclined toward the imaging aircraft and that, whereas there is much shadowing, as one would expect in an area of high relief and steep slopes, not all of the low returns are shadows. This behavior indicates an all-or-none type return due to some variable factor and this factor appears to be the local slope orientation of the terrain.

The very low depolarized returns from the Navajo as seen in the HV image in Figure IX allows easy discrimination of the Navajo outcrops from those of adjacent units. The outcrop pattern of the Navajo as expressed by low cross-polarized returns, shows a very close correlation to that appearing on the 1:250,000 geologic map of southeastern Utah compiled by Hintze and Stokes (1964).

# TABLE I

## SUMMARY OF SYSTEM PARAMETERS AND TARGET PROPERTIES FOR AREAS PRODUCING POLARIZATION ANOMALIES

| AREA | FLIGHT-PASS | TRANSMITTED POL. | RANGE | LOOK | ROCK TYPE | AGE | VEGETATION | INTERNAL CHARACTERISTICS | SURFACE CHARACTERISTICS | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| Cody Mountains<br>San Bernardino Co.<br>California | 102 | H | Mid-Far | SE | Basalt and Andesite and Related Frag-mental Volcanic Formations | Tertiary Oligocene or Miocene | Very Sparse | Variable | All Rock Types Involved have Surfaces Littered with Large Angular Volcanic Fragments hav-ing Planar Faces, Sharp Edges and Desert Varnish Coatings. | |
| Inyo Craters<br>Mono Co. California | 2<br>3<br>100-4<br>6<br>7<br>8<br>1<br>101-2<br>3 | V<br>V<br>V<br>V<br>V<br>V<br>H<br>H<br>H | Near<br>Mid<br>Near<br>Mid<br>Far<br>Far<br>Near-Far<br>Mid<br>Mid | E<br>W<br>E<br>E<br>W<br>E<br>W<br>E<br>W | Rhyolite | Quat-ernary | Absent | Variable from Highly Vesicular Pumice to Dense Obsidian Includ-ing Blocks of Interlayered Pumice and Obsidian. | Extremely Blocky, Blocks Large up to Several Feet in Diameter, Faces Smooth and Planar, Edges Sharp. | Inyo Craters are Youthful Rhyolite Domes Mantled with Blocks of Pumice and Obsidian and Unaltered by Weather-ing. |
| Malpais Flow<br>San Bernardino Co.<br>California | 102-1<br>102-2<br>102-3 | V<br>V<br>H | Far<br>Near<br>Mid-Far | SW<br>NE<br>SE | Basalt | Quat-ernary | Scattered Low Shrubs and Desert Grasses | Vesicular Microcrystalline with Small Pheocrysts of Olivine and Labradorite. | Blocky Basalt with Polyhedral Blocks Averaging 50 cm. in Diameter, most Coated with Desert Varnish. | Malpais Basalt is Quite Similar in Appearance to Nearby Sunshine Basalt. |
| Mecca Hills<br>Riverside Co.<br>California | 102 | H | Near-Mid | SW | Palm Springs Formation Terrestial Arkose | Pliocene | Absent | Grain Size Variable Fine Sand to Gravel. Contains Thin Interbedded Clays of Minor Importance. Arkose is Friable and Massively Bedded. | Weathers into Hard-Rock Badlands Generally Devoid of Rubble with many Smooth Rounded Forms. | Palm Springs Formation Strikes Parallel to Flight Path and Dips Steeply to the Southwest. |
| Mono Craters<br>Mono Co.<br>California | 1<br>2<br>3<br>4<br>100-5<br>6<br>7<br>8<br>1<br>101-2<br>3 | V<br>V<br>V<br>V<br>V<br>V<br>V<br>V<br>H<br>H<br>H | Near-Far<br>Near-Mid<br>Mid-Far<br>Near-Mid<br>Far<br>Far<br>Far<br>Far<br>Mid<br>Far<br>Mid-Far | N<br>E<br>W<br>E<br>W<br>E<br>W<br>E<br>W<br>E<br>W | Rhyolite | Quat-ernary | Generally Sparse especially on Flows Lacking Ash Deposits | Variable, from Highly Vesicular Pumice to Dense Obsidian includ-ing Blocks of Interlayered Pumice and Obsidian. | Extremely Blocky on Exposed Dome and Coulee Surfaces. Blocks Large up to Two Meters in Diameter Faces Smooth and Planar, Edges Sharp. | Tonal Reversals are Restricted to Younger Blocky Flows and Domes that lack Surficial Deposits of Pumiceous Ash. Nearby Inyo Craters Identical in Surface Expression. |
| S.P. Lava Flow<br>Coconino Co.<br>Arizona | 103 | H | Mid | E | Basalt | Recent | Sparse-Isolated Low Shrubs Short Stemmed Grasses | Dense, Fine Grained Basalt Finely Vesicular and Porphyritc in Texture with Phenocrysts of Plagioclase Feldspar and Olivine. | Blocky Basalt. Blocks Polyhedral with Smooth Faces and Sharp Edges. Blocks range from 30 to 100 cm. in Diameter. | Flow is Very Recent and Lava is Virtually Unaltered. |
| San Rafael Swell<br>Emery Co.<br>Utah | 92 | H | Near-Far | SW | Navajo Sandstone | Jurassic | Absent | Composed of Fine Grained Well Sorted Quartz Sand. Large Scale Cross Bedding. | Smooth Hard Rock Badlands Shaped into Large Rounded Forms Largely Devoid of Soil, Rubble and Vegetation. | Navajo Exposed on Monoclinal Uplift Dip Varies Considerably and Direction of Dip Swings from the NE to the SE. |

# TABLE I (Completed)

| AREA | FLIGHT PASS | TRANSMITTED POL. | RANGE | LOOK | ROCK TYPE | AGE | VEGETATION | INTERNAL CHARACTERISTICS | SURFACE CHARACTERISTICS | REMARKS |
|---|---|---|---|---|---|---|---|---|---|---|
| Southern Muddy Mountains<br>Clark Co.<br>Nevada | 103 | H | Near-Far | S | Aztec Sandstone | Jurassic ? | Absent | Composed of Fine Grained Well Sorted Quartz Sand. Large Scale Cross Bedding. | Smooth Hard Rock Badlands Shaped into Large Rounded Forms Largely Devoid of Soil, Rubble and Vegetation. | Aztec Sandstone is Generally Regarded as a Westward Extension of Navajo Sandstone, both are Identical in Lithology and Surface Expression. |
| Sunshine Lava Flow<br>San Bernardino Co.<br>California | 101-1<br>1<br>2<br>102-3<br>4<br>5 | V<br>V<br>V<br>H<br>H<br>V | Mid<br>Far<br>Near<br>Far<br>Near-Mid<br>Far | SE<br>SSW<br>NNE<br>SSW<br>NE<br>SW | Basalt | Quaternary | Sparse | Vesicular Porphyritic Alkali-Olivine Basalt with Phenocrysts of Olivine. | Blocky Basalt Composed of Angular Blocks Generally 75 cm. or Less in Diameter which Form a Hummocky Surface. Most Older Surfaces are Coated with Desert Varnish. | |
| Three Sisters Region<br>Lane and Deschutes Co.<br>Oregon | 98-1<br>98-2 | H<br>H | Near<br>Near | E<br>W | Dacite<br>Dacite | Quaternary | Absent | Varies from Pumice to Obsidian with Both Rock Types Inter-layered in Many Instances. | Dacite Occurs as Several Volcanic Domes and Thick Stubby Flows. Surfaces are Composed of Shattered Blocks of Obsidian and Pumice which are up to Two m in Diameter and have Smooth Faces and Sharp Edges. | Dacite Domes are Identical in Appearance to Rhyolite Flows and Domes found at Mono and Inyo Craters. |
| | 98-2 | H | Near-Far | W | Basalt | Quaternary | Absent | Dense Basalt Generally Scoraceous but Quite Variable from Flow to Flow. | Blocky Basalt with Planar Faces and Angular Edges. Smoothness of Faces is Dependent upon Degree of Vesicularity North-ward Flowing Flows are Generally less Vesicular than those that Issued from Belknap Crater. | |
| Ticaboo Creek<br>Garfield Co.<br>Utah | 93 | H | Near-Far | N | Navajo Sandstone | Jurassic | Absent | Composed of Fine Grained Well Sorted Quartz Sand. Large Scale Cross Bedding. | Smooth Hard Rock Badlands Shaped into Large Rounded Forms Largely Devoid of Soil, Rubble and Vegetation. | Navajo Sandstone Essentially Flat Lying Exposed in Highly Dissected Area Adjacent to Colorado River. |
| Twin Buttes<br>Pima Co.<br>Arizona | 104 | H | Near-Mid | NW | Olivine-Pyroxene Andesite<br>Hornblende-Biotite Rhyodacite<br>Pyroxene Rhyodacite | Tertiary<br>"<br>"<br>Tertiary | Sparse Low Shrubs and Cacti<br>Short Grasses and Ocotillo | Fine Grained and Porphyritic | All Three Rock Types Weather to Form Outcrops Covered with Blocky Rubble. Blocks Variable in Size Generally Polyhedral but with Corners and Edges Somewhat Rounded. | O. P. Andesite Forms a Number of Small Buttes E of Tinaja Peak. Hornblende Biotite Rhyodacite Occurs at Tinaja Peak and Hilly Area to the South. Pyroxene Rhyodacite Lacks Significant Topographic Expression. Occurs in Three Isolated Areas Farther South. |
| Waterpocket Fold<br>Garfield Co.<br>Utah | 93 | H | Near-Far | N | Navajo Sandstone | Jurassic | Absent | Composed of Fine Grained Well Sorted Quartz Sand. Large Scale Cross Bedding. | Smooth Hard Rock Badlands Shaped into Large Rounded Forms Largely Devoid of Soil, Rubble and Vegetation. | Navajo Exposed as Hogback Ridge Striking NW and Dipping to the NE. |

Flight numbers refer to NASA sponsored AN/APQ-97 flights conducted during the Earth Resources Program in 1965 and 1966. Some areas were subject to several passes. Range location is described in relation to the nadir of the aircraft. Look refers to look-direction.

CHAPTER 4

# DISCUSSION

System parameters and target properties are summarized in Table I for those polarization anomalies subject to intensive study in this investigation. All areas were visited in the field with the exception of the Navajo Sandstone outcrops whose surface characteristics were interpreted from aerial photographs and whose internal characteristics were summarized from various published reports. Both characteristics were judged to be identical to those of the Aztec Sandstone. Some areas, such as Mono Craters and the Sunshine lava flow were imaged on one or more flights and in several passes. These different passes usually incorporated different system parameters such as transmitted polarization, which is either horizontal or vertical,look direction, and range location. Despite these varying parameters, all the areas listed behave the same with respect to polarization, producing darker cross-polarized images.

Target properties, like the system parameters, are found to be highly variable from one anomalous area to the other. As previously stated, rock types associated with lower cross-polarized returns are found to be wide-ranging. Among these are volcanic rocks including rhyolite, rhyodacite, dacite, andesite, and basalt; in addition, breccias and fanglomerates composed of andesitic and basaltic fragments are also associated with tonal reversals. In other areas, sandstones are responsible for low cross-polarized returns, these include the well-sorted quartzose sandstones, Navajo and Aztec as well as the arkosic Palm Springs Formation. The ages of these various rock types are predominately Tertiary or Quaternary, the exceptions being the Navajo and Aztec sandstone which are considered Jurassic in age.

Soil and vegetation in the areas under discussion cannot be considered important contributors to the radar return. Vegetation and soil development is suppressed in these areas for one or more of three different reasons; extreme aridity, youthfulness of the landscape, and weathering habit. Aridity accounts for the scant vegetation in the area of the Cady Mountains, the Mecca Hills, and other areas in the Mojave Desert of California. Other areas represent youthful lava flows upon which soil and vegetation has not yet developed. Examples are the Quaternary lava flows of the Three Sisters region which are unvegetated despite being in a relatively humid climate. The massive friable sandstones such as the Aztec and Navajo are easily eroded on a grain by grain basis and in areas of high relief fail to develop soils. This results in areas of hard-rock badlands.

The only area in which vegetation could possibly be considered a factor in radar return is the Twin Buttes area of southern Arizona. This area lies partially in desert grasslands and as previously stated these grasslands are verdant during the seasonal wet periods. However, the area was imaged during the fall dry season when the grasses are dead and here also vegetation can be considered an unimportant target parameter.

Thus in all the areas under investigation, the only target properties involved in producing the recorded radar returns are those of the rocks themselves. These target properties have been divided into two general classes in Table I, relating to the internal and surficial makeup of the rocks involved.

Internal characteristics of rocks were found to be quite variable, not only between study areas but within as well. The volcanic rocks of course, are generally fine-grained. The grain-size was the largest in the case of some porphyritic basalts and ranged downward to fine-grained and microcrystalline in others with the ultimate being the volcanic glass of the Three Sisters dacite and Mono Craters rhyolite which lacks crystals. Vesicularity of the volcanics is quite variable, the extremes being the dense volcanic glass and the lightweight pumice found in association at Mono-Inyo Craters and in the Three Sisters area. In basalts, the vesicularity is very fine in the case of the

S. P. Lava, however other basalts displayed much larger vesicles. Vesicularity was sometimes found to be quite variable within a given flow, not only in the obvious case of the rhyolites and dacites but also in some basaltic lavas.

In the case of the sandstones, grain-size is quite uniform in the fine-grained, well-sorted Aztec and Navajo sandstones. However, the Palm Springs formation is quite variable being poorly sorted and including many conglomeratic lenses. The Aztec and Navajo are very massive and uniform and except for large-scale cross-bedding, lack sedimentary structure. The Palm Springs is also massively bedded but also includes some small shale partings.

Of course, sandstones and volcanics share very few lithologic characteristics. The arkosic Palm Springs formation and the most acidic volcanic rocks approach similarity in mineralogic composition, and the Aztec and Navajo sandstones share grain size comparable to that of some of the basaltic lavas. Other than these weak analogies, no compositional or textural similarities can be found between the sandstones and volcanics under study. Nor can such similarities be found among the volcanics themselves. Most common compositions, grain sizes, and degrees of vesicularity associated with volcanic rocks are represented in the group of rocks found to be responsible for anomalous cross-polarized returns. In fact, the two rocks which possess the most strikingly different internal characteristics, obsidian and pumice are found to produce identical radar returns.

Unlike the other target properties, the surface characteristics of the rocks studied show some consistency. All the volcanic rocks investigated possess surfaces that are dominated by polyhedral blocks of lava. The acidic and intermediate lavas were erupted in the form of volcanic domes and short, thick flows or coulees. These eruptive forms are discussed at length by Williams, who states, "Few features of domes are more typical than the breakup of their crusts during upheaval. By this process, their surfaces are littered with piles of angular and subangular blocks...." (1933, p. 133). This description is particularly applicable to the rhyolites of Mono and Inyo Craters and the dacites of South Sister Peak, which have been described previously.

Some older intermediate volcanic rocks, tertiary in age, also exhibit surfaces covered by angular blocks. Although actual eruption of these rocks may have initiated the obvious shattering, weathering has undoubtedly contributed. The rounded corners and edges observed on the Tertiary lavas in the Twin Buttes area attest to this. The volcanic breccias and fanglomerates observed in the Cady Mountains area reflect considerable weathering and mass movement yet the volcanic fragments remain polyhedral and create a surface configuration strikingly similar to that of the blocky lavas. The remaining volcanic rocks studied are all basaltic. More importantly, these basalts are all block lavas. None of the basalts associated with lower cross-polarized returns were found to contain significant amounts of aa or pahoehoe.

Finch proposed the term "block lava" to describe that class of lavas that could not be adequately described by the terms aa and pahoehoe. According to Finch (1933, p. 769) "A characteristic of aa is the spiny or clinkery surface of most of the individual fragments. Although the block lava, when viewed from a distance, may appear somewhat like aa, a close view shows a lack of true aa characteristics. Also the individual blocks have conspicuous though rough dihedral angles." The term block lava has since been adopted by others who have described extrusive rocks including Jones (1943) and MacDonald (1953 and 1967). These descriptions accurately describe the basaltic lavas visited in the field which are found to produce low cross-polarized returns. Although the vesicularity of these basalts was variable it was never present to such a degree as to destroy the planar aspect of the individual block faces. This blocky character was omnipresent among the basalts investigated in the field.

Thus all the volcanic rocks; the rhyolites and dacites, both pumice and obsidian; the intermediate rocks including the fragmental volcanic formations; and the basaltic lavas share the same general surface characteristics. Polyhedral blocks of lava ranging from 25 cm. in diameter upward dominate the land surface in all cases.

The sandstones differ from the lavas in surface expression but are similar among themselves. Their weathering habit is such that they tend to erode into areas of hard-rock badlands. These outcrops can be characterized as being made up of smooth rounded forms of bare sandstone devoid of rubble, soil, and vegetation. The roughness of these rock surfaces is no greater than the average grain size of the rocks. The Aztec and Navajo are composed of fine well sorted quartz sand. The Palm Springs Formation is less well sorted and, on the average, coarser grained. Yet the prevailing roughness of their respective rock surfaces do not differ to any appreciable degree.

CHAPTER 5

# CONCLUSIONS

From analysis of radar imagery and studies in the field, it is concluded that surface configuration is the factor responsible for the observed low cross-polarized returns. The mechanism involved may be characterized as being specular or near specular non-depolarized reflection from planar rock surfaces.

Surface configuration is the only target property that can be considered consistent among the rocks investigated. Although the sandstones and the volcanic rocks differ in surface expression, they can be related by a facet model of reflection. By this model, the surface of the ground is considered being composed of small flat planes (Moore, 1969, p. 10). In the case of the blocky surfaces of the volcanic outcrops the facets are real and observable. The sandstones form outcrops made up of rounded forms with radii of curvature that are much larger than the wavelength of Ka-Band radar (approximately 0.87 cm). These surfaces can be decomposed into many tangent planes that are similar to the faces of the lava blocks in being smooth and having dimensions much larger than the wavelength. These smooth rock surfaces dominate the recorded radar returns.

The mechanism involved in producing the anomalously low cross-polarized returns can be understood by using the sandstones as examples, in particularly the Navajo Sandstone in Figure IX. These sandstones weather to form smooth rock surfaces that are often larger than the minimum resolution of the AN/APQ-97 SLAR system (approximately 50' in the images under study). The Navajo outcrops in the Ticaboo Creek area in the like-polarized image of Figure IX have a speckled appearance. As previously stated, the bright specks represent high returns from those surfaces that are inclined toward the imaging aircraft. Dark areas represent areas of shadow as well as rock surfaces that are not properly oriented.

Such sensitivity of radar return to slope orientation can be explained by specular reflection from the bare-rock surfaces. Fine-grained, unconsolidated sediments are known to be specular reflectors but because of the near horizontal attitude of their surfaces the radar energy of a side-looking system is reflected into space, away from the receiving antennas. The silts and clays of playas and areas of alluvial as well as windblown sand reflect the impinging radar in this manner and as a result, appear dark on both like- and cross-polarized images of Ka-band radar. The Navajo sandstone, because of its remarkably uniform texture and grain size and unusual weathering habits is capable of producing extensive areas of bare-rock outcrop that are little different from areas of unconsolidated sands in surface roughness and composition Thus, one would expect both materials to reflect a radar pulse in a similar manner, specularly. The one big difference between consolidated and unconsolidated fine-grained sediments is the attitude of their surfaces. Unlike loose sediment, indurated rocks are capable of supporting their own weight and their surfaces may vary markedly from the horizontal in orientation. The Navajo, because of its tendency to weather into broad rounded forms, is capable of producing bare-rock surfaces of virtually every possible orientation.

If the radar reflection from these surfaces is specular, a multitude of reflection paths are also possible. Thus in the maze of bare-rock surfaces the Navajo produces, when extensively dissected as in Ticaboo Creek Canyon, one would expect a number of such surfaces to have the proper orientation to specularly reflect a radar signal back to its source. Such surfaces would produce high returns and bright radar images. Smoot rock surfaces that are not orthogonal to the propagation direction of the radar beam would specularly reflect it in another direction with little of the radar energy reaching the receiver and would thus produce dark radar images. Such a mechanism of radar return explains the speckled appearance of Navajo outcrops on the like-image of the Ticaboo Creek area and accounts for the correlation of the bright specks with those rock surfaces oriented toward the imaging aircraft.

In addition, specular reflection could explain the low returns the Navajo exhibits in the cross-polarized Ticaboo Creek image. Rock surfaces smooth enough to specularly reflect a radar beam are likely to be poor depolarizers of radar energy, thus, an incident radar beam will maintain its original polarization upon reflection. A target reflecting radar in this manner will produce a bright like-polarized image in which the polarization received is the same as the polarization transmitted, however the absence of depolarization will result in a dark cross-polarized image in which the orthogonal component of depolarization is not received. This is the type of multipolarization behavior that the Navajo exhibits in the Ticaboo Creek imagery and is similar to the other areas which produce anomalous differences; bright like-polarized images are simultaneously produced with dark cross-polarized images.

The volcanic rocks possess highly faceted surfaces. Like the sandstones, these facets are many wavelengths across; however they remain much smaller than the resolution of the system. The reflection from these individual facets would be the same as from the sandstone surfaces since they are comparable in smoothness and larger than the wavelength. For such facets most of the return occurs at near normal incidence (Moore, 1969, p. 10) . The appearance of the volcanic formations on radar imagery represents an averaged return that is dominated by those rock faces that are oriented normal to the impinging radar signal. Within a given resolution cell on one of these volcanic outcrops are likely to be several faces with the proper orientation. Because of the specular reflection from these surfaces their like-polarized returns are strong. Similarly, reflections from other surfaces are directed away from the receiving antennas and are not recorded. Since the normally oriented faces dominate the return, their poor depolarizing characteristics result in low cross-polarized returns. This mechanism is illustrated in Figure 5, in which two terrain types are represented, a rough gravelly surface and a highly faceted blocky surface. The first surface produces a diffuse and depolarized reflection that is recorded on both like and cross polarized images; the second, like the blocky lavas, is a poor depolarizer and produces specular non-depolarized reflections and dark cross-polarized images result.

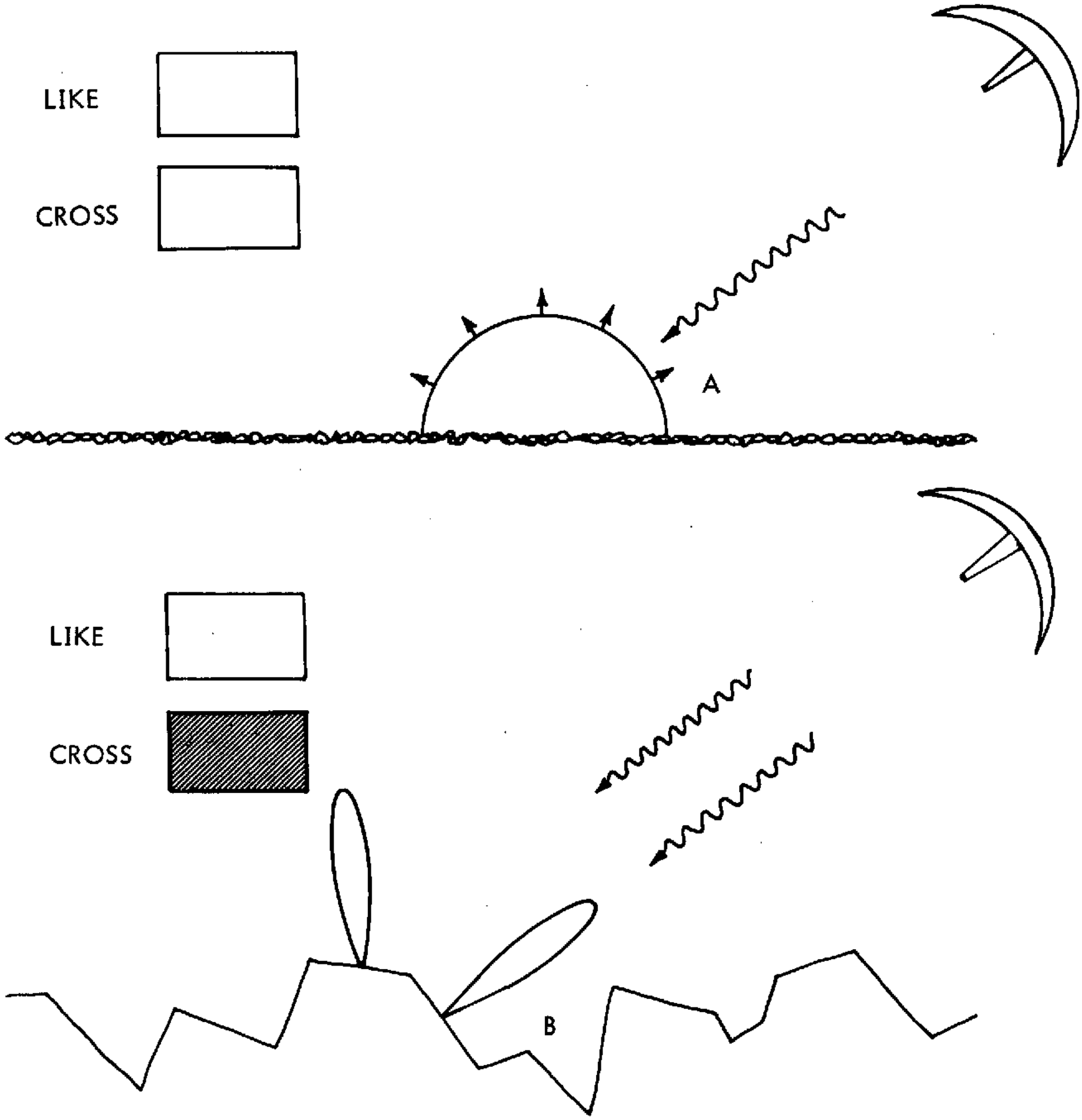


Figure 5. Like- and Cross-Polarized Returns Resulting from Diffuse Reflection (A) and Specular Reflection from a Highly Faceted Surface (B).

Planar surfaces are randomly and uniformly distributed in the blocky outcrops of the volcanic rocks. This explains the lack of dependence of tonal reversal upon look direction and surface orientation. Because it is the surfaces oriented normal to radar beam which produce the low cross-polarized returns it makes no difference if the impinging radar is horizontally or vertically polarized. Both polarizations vibrate in the plane of the rock surface and neither is likely to be strongly depolarized. Hence the tonal reversals occur on HH-HV images as well as on VV-VH images.

In conclusion, the diverse rock types producing similar multi-polarized radar returns are found to share certain features; planar rock surfaces that are large in comparison with the wavelength of the incident radar are abundant and detrital material and vegetation are of secondary importance. The planar surfaces appear to significantly contribute to the returning radar energy with this energy maintaining a constant polarization. The outcrop areas are of sufficient size and sufficiently uniform character to be delineated on small scale K-band imagery.

These findings reinforce the notion that surface configuration is the most important terrain related factor in the production of radar images. This is especially true in radar studies of rocks and surface materials. In the analysis and interpretation of anomalous radar images, surface configuration should be the first terrain parameter evaluated.

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